VOL. 11 No. 4, pp. 101-132 OCTOBER 1949

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

CAUSES OF POROSITY IN WELDS

by J. D. FAST.

621.791.056:620.192.34

When consideration is given to the very great importance of electric arc welding in engineering it is surprising that this process should be based upon such scanty scientific grounds. This is manifest in the number of phenomena still unexplained and the surprises, sometimes unpleasant, encountered in practice. With the aid of thermodynamic and metallurgical theories the writer endeavours to throw some light upon one of the most common causes of disappointments in the making of welds.

In electric arc welding under certain conditions the welds are likely to be porous. It may be taken as an established fact that this porosity must be related to the formation of gas bubbles in the metal during the process of welding, but no deeper insight has yet been obtained into the underlying phenomena. For instance, no explanation at all has yet been given for the fact that certain types of welding electrodes are particularly sensitive, as regards porosity, to the presence of relatively small quantities of sulphur in the metal to be welded. For instance from investigations carried out by J. ter Berg [1]) it appears that with type Ph 50 electrodes highly porous welds are obtained if the basic metal contains 0.1% sulphur, whereas with type Ph 56 electrodes even free-cutting steels containing about 0.25% sulphur can be welded without the welds being porous [2]).

In this article we shall outline a mechanism whereby porosity may arise in arc welds. The rate at which gas bubbles are formed and any factors which hinder their formation will play an essential part in this mechanism. Based upon this picture, an attempt will be made to explain the mysterious action of sulphur and some other phenomena hitherto not understood.

The formation of cavities in solidifying metal

The solubility of most gases in metals diminishes as the temperature drops, and when the freezing point of the metal is reached it may even show a sudden drop. This may be seen, for instance, from the curves in *fig. 1* showing the solubility of hydrogen and nitrogen in iron at a pressure of 1 atm.

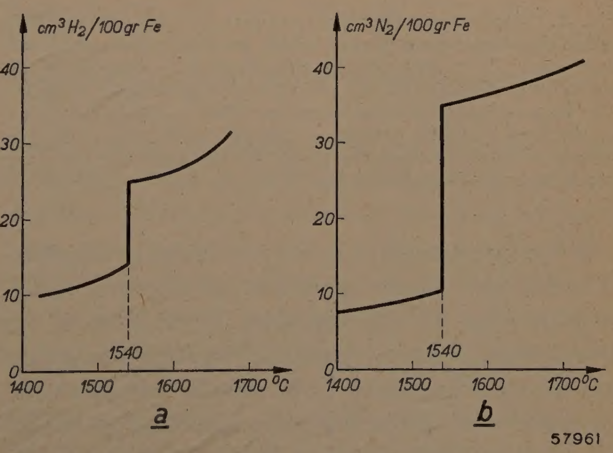


Fig. 1. Solubility of hydrogen (a) and nitrogen (b) in iron as a function of the temperature, showing the quantities of gas (expressed in volume at 1 atm. and 0 °C) absorbed by 100 grams of iron in atmospheres of hydrogen and nitrogen of 1 atm.

---

[1]) J. ter Berg, Philips Techn. Rev. 7, 91-93, 1942.

[2]) For a description of the composition of the various types of welding electrodes see J. D. Fast, Philips Techn. Rev. **10**, 114-122, 1948 (No. 4). As appears from this article, the Ph 56 electrode is identical in composition to the older type Ph 55. The only difference is that the coating materials of the Ph 56 are applied around the core in two different layers.

A metal which in the molten state has absorbed gases will therefore usually have to give off some of this gas again when cooling down and especially when freezing. The excess gas present in the metal in the atomic state can leave the metal in two ways: 1) the atoms may diffuse through the liquid or through the metal meanwhile solidified to the outer surface and there recombine into gas molecules; 2) gas bubbles may form in the liquid metal, these growing in size owing to the diffusion of atoms from the surrounding metal, and rising to the surface under the influence of the hydrostatic pressure.

It will depend upon the rate at which these two processes take place and upon the rate of freezing whether cavities occur in the solidifying metal. Some experiments will explain this.

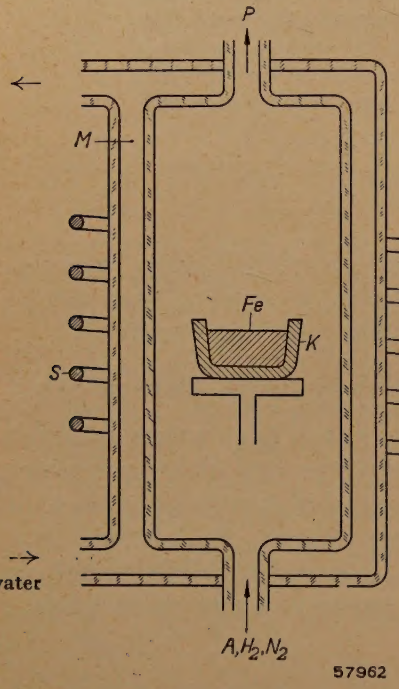


Fig. 2. Diagram showing the arrangement for melting and solidifying small quantities of iron in an atmosphere of certain pure gases. The iron (*Fe*) is contained in a crucible *K* of aluminium oxide placed in a glass vessel with a double wall *M*. The iron is heated by the high frequency method by means of the coil *S*; rapid cooling is brought about by passing a stream of water through the jacket *M*; the gases are led in at the bottom and pumped out at *P*.

100 gram portions of iron were melted in crucibles of refractory oxide by means of high-frequency heating (*fig. 2*), the crucibles being held in an atmosphere of carefully purified hydrogen or nitrogen at 1 atm pressure. The molten iron becomes saturated with gas and is then cooled down. From fig. 1 it can be seen that in the solidification of 100 grams of iron, in equilibrium with hydrogen at 1 atm, 11 cm^3 H_2 (volume converted to 0 °C) had to escape from the metallic solution, i.e. 72 cm^3 H_2 at the prevailing temperature of 1540 °C. With nitrogen this volume is still greater. Thus in our experiments the volume of the gas liberated at the freezing point is much greater than the volume of the iron itself!

The experiment was repeated in vacuum and in an atmosphere of argon, which is quite insoluble both in liquid and in solid iron.

Four small lumps of iron obtained in this way by melting and rapid cooling are shown in *fig. 3a* and, sawn through, in fig. 3*b*. As was to be expected, the lumps produced in vacuum and in argon showed no cavities or pores, whereas those produced in atmospheres of hydrogen and nitrogen show large cavities. The formation of these cavities could be observed during the experiments through the glass wall of the vessel. Since the molten iron cooled down by radiation and convection, it solidified first on the surface. Owing to the sudden drop in solubility at the freezing point the solidifying iron retains little gas in solution, so that the liquid iron underneath becomes temporarily supersaturated with gas. As a result a vigorous formation of gas bubbles takes place in the liquid iron and it can be observed how at a certain moment the solidified surface is in places pushed upwards. In some of our experiments, repeated several times, the liquid then broke through the protruding crust and flowed over the solid surface with "boiling" phenomena. Thus there may ultimately be not only cavities underneath the surface but also holes in the surface.

In the case of such an "eruption" it may happen that the protrusion first formed melts away again; see *fig. 4a* and *b*. In some experiments this phenomenon of the formation and collapse of the protruding surface even repeated itself several times. This shows a striking resemblence, in miniature, to volcanic eruptions where a liquid lava supersaturated with gas breaks through a solid crust and flows outwards.

In a further series of experiments the molten iron was cooled more slowly by somewhat insulating the crucible (placing it in a second crucible with the surrounding space filled with powdered aluminium oxide). As shown in *figs 5a* and *b*, a lump of iron formed in this way in an atmosphere of hydrogen has but relatively few holes, whereas one formed in nitrogen shows the same phenomena as found in the case of rapid cooling. The explanation of this is that when the metal solidifies more slowly the first process mentioned above — diffusing of the dissolved atoms through the liquid and solid metal followed by recombination at the surface — has a better chance of assisting the removal of the surplus gas. In the case of hydrogen this process takes place

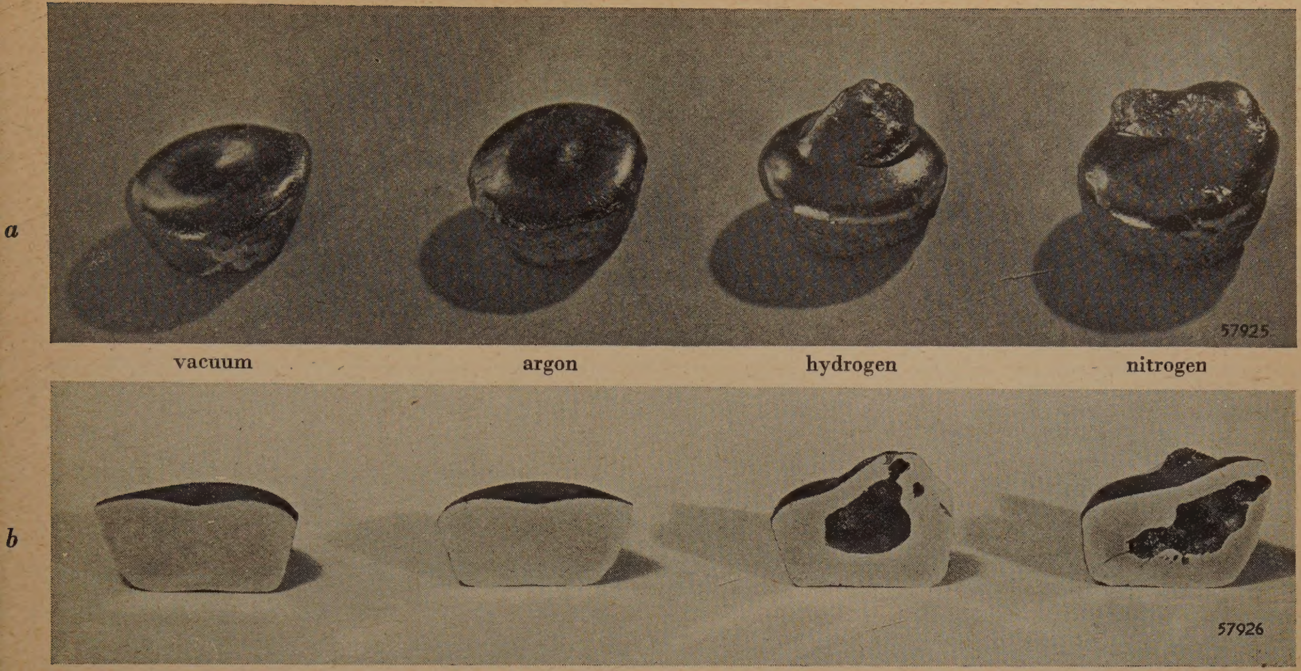


Fig. 3. *a*) Four lumps of iron melted and rapidly cooled respectively in vacuum, in argon, in hydrogen and in nitrogen. *b*) The same lumps sawn through. The lumps obtained by melting in vacuum and in argon show no cavities, whereas those obtained by melting in hydrogen and nitrogen show the traces of strong gas formation in the course of solidification.

relatively quickly [3]), so that this gas can escape from the supersaturated solution without large bubbles being formed. In the case of nitrogen the diffusion is much slower and, moreover, according to fig. 1 the supersaturation is much greater, so that the situation is not appreciably improved by the slower rate of solidification.

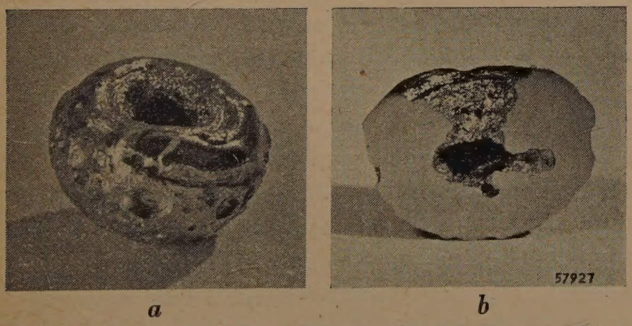


Fig. 4. A lump of iron melted and solidified in hydrogen analogous to that in fig. 3, which behaved as a miniature volcano in the process of solidification and showed the formation of a "crater" and "stream of lava".

The experiments described throw some light upon some of the factors taking part in the formation of pores when welding. But the situation in welding is in several respects different and more complicated. There is one difference which we must discuss at this stage: in welding, the iron deposited does not solidify inwards but outwards, beginning at the interface between the workpiece and the shallow pool of molten metal.

If in this case bubbles are still being formed while the outer layer of metal (adjacent to the floating slag) is about to solidify, there will obviously be holes in the final weld surface or, in a less serious case, small depressions. But even if no more gas bubbles are formed at that stage and the solidified surface therefore shows no defects, there may nevertheless still be internal cavities. To understand this we must look more closely into the actual process of the formation of the gas bubbles.

This takes place at the boundary between the solid and the liquid metal, as we shall see in the following sections. So long as they are small the bubbles adhere to this interface and it is not until they have grown beyond a certain size that they can detach themselves from the interface and rise. It may, however, happen that the bubbles grow more slowly than or at most not much quicker than corresponds to the displacement of the said interface as the process of solidification proceeds. The bubbles are then held in the metal and take the shape of elongated gas inclusions with their longitudinal axis roughly perpendicular to the solidifying surface. This is illustrated in *fig. 6*.

---

[3]) See for instance J. D. Fast, Experiments on the permeation of gases through metal walls, Philips Techn. Rev. 7, 74-82, 1942.

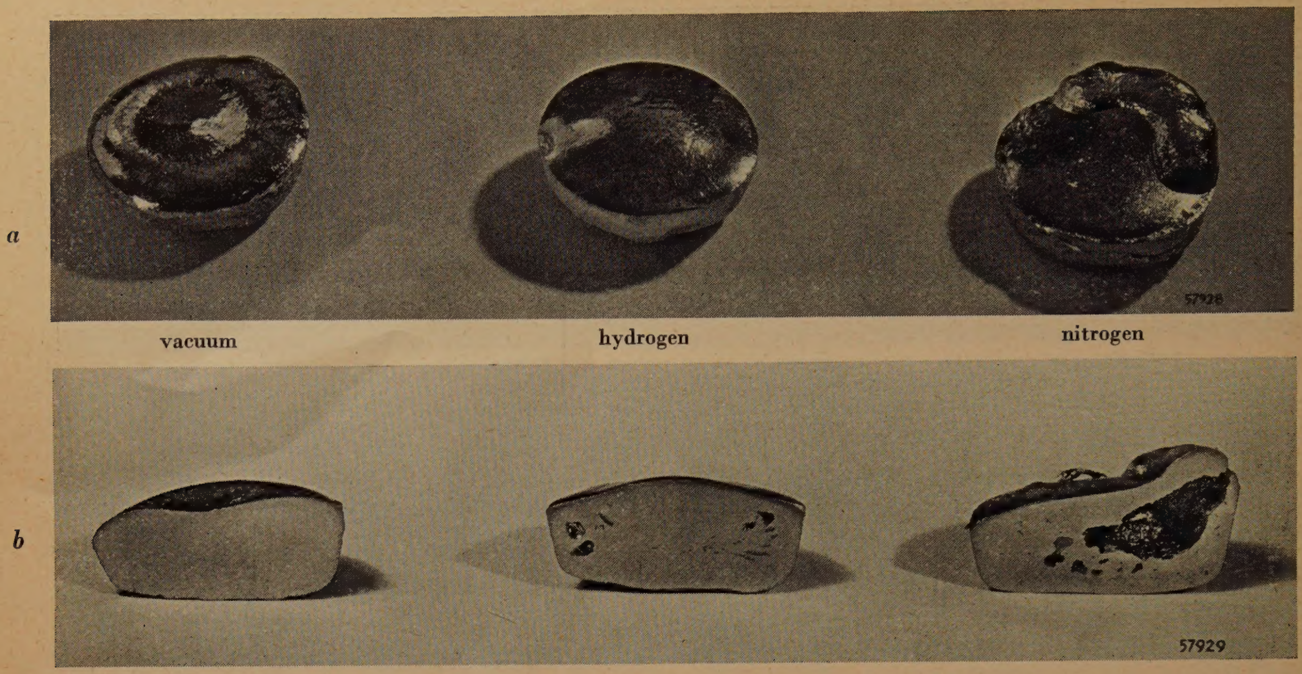


Fig. 5. Three lumps of iron melted and solidified respectively in vacuum, hydrogen and nitrogen. These lumps were cooled down much more slowly than those in fig. 3. In the case of the lump melted in hydrogen most of the dissolved gas was able to escape through diffusion, but nitrogen diffuses too slowly to show any difference compared with the corresponding lump which solidified rapidly.

Experiments where this phenomenon occurred, due to the oxygen content of the deposited metal being reduced by the addition of Al, Ti or Zr, have been described in the article quoted in footnote [2]).

As a particular case, in the race between a growing gas bubble and the advancing interface it may happen that, while the bottom part of the bubble remains held in the metal, at the top where the bubble has already grown considerably in size at a certain moment a part of it breaks away. The liquid metal flowing inwards then causes at that place a constriction in the gas cavity which is meanwhile growing further again. This phenomenon may repeat itself several times, causing the formation of cavities with alternating constrictions and expansions, which may occur not only in welds but also in steel ingots [4]).

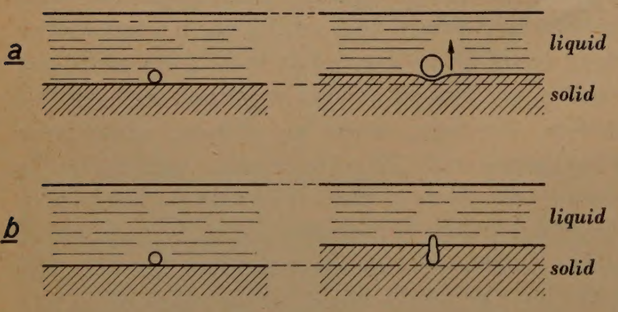


Fig. 6. In welding a pool of molten metal is deposited on the solid metal of the workpiece. During the process of solidification the interface between the solid and the liquid metal moves gradually towards the surface. Gas bubbles are formed preferentially on the interface. If they grow quickly enough then they soon break away and rise to the surface (*a*). If they grow too slowly they are apt to become enclosed by the solidifying metal and then give rise to the formation of cavities (*b*). This process may be promoted by the interface between the solid and the liquid not advancing in a smooth plane, as drawn in the diagram for the sake of simplicity, but more or less irregularly due to the crystals (dendrites) growing in a criss-cross fashion and with many spurs.

These considerations lead to the rather surprising conclusion that porosity in welds may be due not only to an abnormally strong evolution of gas but possibly also, in the case of normal or even subnormal quantities of gas in the metal, to a retardation of the evolution of gas. Such a retardation may on the one hand cause the evolution of gas to be postponed too long, so that it is not completed by the time the outermost layer of metal solidifies, while on the other hand it may delay the growth of the gas bubbles, causing them to remain held in the solidifying metal.

We shall now consider firstly the conditions under which evolution of gas can take place in the deposited metal when welding, and secondly under what conditions there may be a hindrance to the evolution of gas as referred to above.

Conditions for the evolution of gas in the deposited liquid metal

Just as was the case in the experiments already described, in the process of welding the molten metal tends to become saturated with gas from the surrounding atmosphere, in particular with oxygen and nitrogen when welding in air. Apart from the likelihood of porosity this is undesirable because it spoils the mechanical properties of the weld [5]). The molten metal is therefore protected as far as possible against the attack of the air by means of a coating round the electrodes. This provides a protective layer of slag on the molten metal (and also around the droplets as they are being transferred). This coating, however, must also produce a powerful stream of gas which gives a steady deposition of droplets and a good penetration. For this purpose the coating contains chemically bound gases which are released when welding: bound water, H_2O, and carbon dioxide, CO_2, in the case of type Ph 50 electrodes, and almost exclusively bound CO_2 in the type Ph 56 electrodes. Due to reaction with reducing metal powders in the coating the Ph 50 releases a mixture of CO_2, H_2O, CO and H_2, whilst the Ph 56 produces a mixture of CO_2 and CO. In the case of the Ph 56 the gases thus evolved have little influence upon the deposited metal: a small quantity of oxygen, 0.03%, is thereby added to the 0.08% — 0.10% of carbon already present. In the case of the Ph 50 the situation is much less favourable: a large amount of the hydrogen contained in the gases is absorbed by the liquid metal (more than 0.0014% by weight) and since this type of electrode contains, among other compounds, iron oxide in the coating, also more oxygen is taken up in the deposited metal (more than 0.1%). Furthermore, there is a fairly considerable amount of nitrogen taken up when welding with type Ph 50 electrodes (about 0.03%).

---

[4]) See also A. Hultgren and G. Phragmen, Trans. A.I.M.E. 135, 133-244, 1939.

Therefore, when welding with the Ph 50, one obtains liquid iron containing dissolved carbon, oxygen, hydrogen and nitrogen together. Such a solution is only stable if there is an atmosphere over the liquid metal containing, among others, CO_2, H_2O, CO, H_2 and N_2 with certain partial pressures. The values of these partial pressures necessary for stability depend both upon the temperature and upon the quantities of dissolved C, O, H and N. If these equilibrium pressures (which we shall term the "latent" partial pressures of the gases in the metal) are greater than the partial pressures actually present in the gas phase, then gas will be released from the metal. We have already seen that this can happen either through diffusion of the gas atoms to the surface of the metal and the formation of gas molecules at that surface, or through the formation of gas bubbles in the liquid. For the latter case — which is of most interest to us here — there is, however, a second requirement: a gas bubble can only exist in the liquid if its internal pressure (which can never exceed the total "latent pressure" of the dissolved gases) is greater than the total pressure of the gas atmosphere over the metal. If, for instance, an extra pressure of argon of say 1000 atm were applied over the metal, gas bubbles could only be formed with a pressure greater than 1000 atm, which means to say that it would be practically impossible for gases to escape via the bubbles, although there had been no change in the position of the equilibrium between the solution and the gas phase. The equilibrium could only be established via the slow process of diffusion and recombination.

When welding in air the total pressure over the metal amounts to 1 atm. The obvious question is how great is the pressure available for the formation of bubbles, i.e. the total latent pressure of the dissolved elements in the liquid metal of the weld.

Latent pressure of the dissolved gases in the deposited metal

The concentrations of C, O, H and N in the iron after welding with the Ph 50 and Ph 56 electrodes have already been indicated roughly in the foregoing section. With these relatively small concentrations it may be assumed with a sufficient approximation that as far as the latent pressures are concerned the dissolved elements do not influence each other. In that case, for a temperature immediately above the melting point of iron (1813 °K) these pressures can be calculated from the concentrations with the aid of the formulae [6]):

$$p_{\mathrm{CO}}^{1813} = 500\,[\%\,\mathrm{O}]\ [\%\,\mathrm{C}]\ \text{atm},$$
$$p_{\mathrm{CO_2}}^{1813} = 580\,[\%\,\mathrm{O}]^2\,[\%\,\mathrm{C}]\ \text{atm},$$
$$p_{\mathrm{H_2}}^{1813} = 1.92\cdot 10^5\ [\%\,\mathrm{H}]^2\ \text{atm},$$
$$p_{\mathrm{H_2O}}^{1813} = 8.8\cdot 10^5\,[\%\,\mathrm{O}]\ [\%\,\mathrm{H}]^2\ \text{atm},$$
$$p_{\mathrm{N_2}}^{1813} = 520\,[\%\,\mathrm{N}]^2\ \text{atm}.$$

For the concentrations in the solidified metal deposited from the Ph 50 let us take the following values which have been found experimentally: 0.06% C; 0.12% O; 0.03% N; 0.0014% H. The

---

[5]) See for instance P. C. van der Willigen, The mechanical properties of welded joints, Philips Techn. Rev. 6, 97-104, 1941.

[6]) These formulae are derived in an article by the present author shortly to be published in Philips Research Reports. Strictly speaking, also oxygen (O_2), methane (CH_4) and many other reaction products in the gas phase should be included, but their equilibrium pressures are all so small that the presence of these products may be ignored.

Table I. Latent partial pressures of the gases which may be formed from the dissolved elements in the weld metal of the Ph 50 and Ph 56 electrodes.

gas	Ph 50 0.06% C; 0.03% N; 0.0014% H		Ph 56 0.08% C; 0.01% N; 0% H	
	upper limit (0.12% O) atm	lower limit (0.043% O) atm	upper limit (0.03% O) atm	lower limit (0.001% O) atm
1	2	3	4	5
CO	3.60	1.29	1.20	0.04
CO_2	0.50	0.06	0.04	0.00
H_2	0.38	0.38	—	—
H_2O	0.21	0.07	—	—
N_2	0.47	0.47	0.05	0.05
Total latent pressure	5.16	2.27	1.29	0.09

latent partial pressures calculated from these values are given in *table I* column 2; column 4 gives the latent pressures similarly calculated from the concentrations of C, O and N found experimentally in the metal deposited from the Ph 56.

In the case of the gases containing oxygen as a component the pressures indicated are to be taken as the upper limit, for in the deposited metal there are also silicon and manganese, which have a great affinity for the oxygen dissolved in the metal. The influence of these components upon the latent gas pressures (available for the formation of bubbles) depends not only upon the concentrations of Si, Mn, etc. in the metal but also upon the composition and amount of the slag, which likewise contains these elements. Since in the process of welding no equilibrium is established between the metal and the slag, it is difficult to determine this influence quantitatively. We shall, however, certainly get a lower limit for the latent pressures if we take into account only that percentage of oxygen which is found in the form of FeO by chemical analysis of the deposited metal. According to investigations carried out by Andrews and by Sloman, Rooney and Schofield [7]) this figure is 0.043% O (0.192% FeO) in the case of electrodes of the type Ph 50, and only 0.001% O in the case of the type Ph 56. The latent pressures of CO, CO_2 and H_2O calculated from these figures are given in columns 3 and 5 in table I.

Adding up the pressures given in the table for the various gases, we get in the case of the Ph 56 a total latent pressure which is certainly not appreciably more than 1 atm. In the case of the Ph 50, however, we find that the latent pressure available for the formation of bubbles at the moment of solidification will lie between about 2 and 5 atm, thus in any case much greater than 1 atm.

From this it might be concluded that when welding with the Ph 50 there is a vigorous evolution of gas in process at the moment of solidification. So, while we began this article with the problem of accounting for the porosity sometimes found in welds, we now find ourselves faced rather with the question why it is that under normal conditions *no* porosity occurs when welding with the Ph 50 electrode, a fact well known from experience.

Formation of gas nuclei

The explanation is fairly simple. A necessary condition for the evolution of gas bubbles has been mentioned above, namely that the pressure in the bubble must be greater than the total gas pressure (p) above the liquid. But this condition is not sufficient. We have entirely disregarded the fact that the formation of a gas bubble entails a disruption of the cohesion in the liquid metal. The forming of the new surface corresponds to an extra "capillary pressure" which is given by $2\sigma/r$, where σ represents the surface tension of the liquid metal and r the radius of the gas bubble. The total pressure inside a gas bubble must therefore exceed a value of

$$P = p + \frac{2\sigma}{r} \quad . \; . \; . \; . \; . \; . \quad (1)$$

before the bubble can grow. (Strictly speaking, there should also be added the hydrostatic pressure of the column of liquid over the gas bubble, but in the shallow pool of the deposited metal we can ignore this pressure.)

A growing bubble must of necessity pass through an initial stage in which it is extremely small. In this stage, according to the formula (1), the required pressure in the bubble is therefore very great. In principle this already provides the explanation for the fact that even at a latent pressure exceeding 2 atm no bubbles are formed in the metal deposited from the Ph 50.

The pressure that would be sufficient to bring this about cannot be derived directly from formula (1), since it is impossible to apply this formula for atomic dimensions. The conception of surface tension is in fact essentially macroscopic and loses its significance when it becomes a question of atomic dimensions. The formation of the nucleus of a gas bubble consisting only of relatively few molecules has to be treated as a statistical problem. Although the required latent pressure cannot be indicated, something may be said about the factors playing a part in the statistical problem.

---

[7]) W. Andrews, Trans. Inst. Welding 8, 119-132, 1945. H. A. Sloman, T. E. Rooney and T. H. Schofield, J. Iron & Steel Inst. 152, 127P-153P. 1945.

One can imagine that now and again gas molecules (CO, H_2, etc.) may be formed in the liquid metal when the atoms migrating in the metal meet under favourable conditions. These molecules will have a very short life, dissociating again into atoms after a short time. For the formation of a very small gas bubble it will be necessary for a gas molecule in the liquid during its short existence to meet a number of other molecules (likewise having a very short life). The chance of the required rapid succession of favourable encounters increases with the concentrations of the atoms and is further proportional to the time available. The question whether or not gas bubbles will be formed depends therefore also upon the rate at which the metal solidifies.

In order nevertheless to get some indication of the latent pressure required for the formation of bubbles, we shall assume, perhaps not unjustifiably, that formula (1) may be applied for a bubble with a radius of 10^{-5} cm. According to the data available the surface tensions of liquid metals are of the order of magnitude of 0.5 newton/m (500 dynes/cm). According to formula (1) the bubble can then only grow if its internal pressure is of the order of 10^7 newton/m^2 (10^8 dyne/cm^2) ≈ 100 atm. Considering the manner in which it is calculated, this value of 100 atm must be regarded as the lower limit for the latent pressure required. It may have to be placed a factor 10 or 100 higher.

Thus the formation of gas bubbles in the interior of the liquid metal is virtually precluded.

This difficulty of the formation of gas nuclei gives rise to the occurrence of many phenomena which have been hardly investigated at all in connection with liquid metals but which are only too well known in the case of water and aqueous solutions. In this connection we would refer for instance to the following experimental evidence. Pure water, from which all "gas nuclei" (minute gas bubbles) previously present have been removed by special treatment, can be heated in a glass vessel with flawless walls to over 200 °C without boiling. A temperature of 200 °C corresponds to a water-vapour pressure of 15 atm, which is apparently still insufficient to disrupt the cohesion of the liquid. Water treated in the same way and placed in a glass vessel under a piston can withstand a tensile stress of even more than 50 atm before a break takes place in the liquid. Further, in flawless glass vessels water can be strongly supersaturated with CO_2 without carbon dioxide bubbles being formed.

With all these phenomena it is essential that the vessel should be of glass and that its walls should be perfectly clean. If the water is contained in a vessel the walls of which exercise a smaller adhesive force upon water than that exercised by glass, then the phenomena occur to a much lesser extent because the cohesion between the liquid and the walls can be broken comparatively easily. In a vessel made for instance of a solid hydrocarbon it is not possible to maintain any marked supersaturation of CO_2 in the water. The bubbles are formed at the "weakest" spot of the system, i.e. at the wall. Similarly, if the formation of bubbles of dissolved gas occurs in liquid iron it will usually take place at the interface between the liquid and the solid. This has been well demonstrated in experiments carried out by Oelsen [8]), where liquid iron was surrounded on all sides by liquid slag. In this case even with a C content of 2% and an O content of 0.035% there was no boiling, that is to say no CO bubbles were formed. The given contents correspond at 1813 °K to a latent pressure of CO of about 13 atm [9])! When an iron rod was immersed in the melt supersaturated with C and O there was a strong evolution of gas, which immediately ceased when the rod was withdrawn.

In the case of welding we shall therefore have to bear in mind that the latent pressure required for the formation of bubbles may be very much reduced at the advancing interface between liquid and solid; this applies particularly for sharp corners and edges of crystals which lie in this interface and which grow as the metal solidifies.

Summary of considerations regarding normal welding with electrodes of the Ph 50 type

In the foregiong it has been shown that when welding with electrodes of the Ph 50 type the dissolved gases have a latent pressure of more than two atmospheres at the moment the weld metal solidifies. The experience that under normal conditions non-porous welds are nevertheless obtained with these electrodes has been explained by the fact that for the formation of gas bubbles an extra pressure is needed which in the case in question exceeds the difference between the latent and the atmospheric pressure, notwithstanding the reduction of the required latent pressure at the interface between the liquid and the solid metal.

---

[8]) W. Oelsen, Stahl und Eisen **56**, 182-188, 1936.

[9]) The formula given above for the CO pressure would yield a pressure of 35 atm. With a C content of 2%, however, this formula can no longer be applied because there is then already a strong interaction between C and O in the melt. This interaction reduces the CO equilibrium pressure, which according to the findings of S. Marshall and J. Chipman (Trans. Amer. Soc. Metals **30**, 695-746, 1942) in the case of 2% C is given by $p_{\mathrm{CO}}^{1813} = 190$ [%O] [%C].

This applies, however, only for the end of the solidification, that is to say for the moment at which the outermost layer of deposited metal solidifies. It is almost certain that in the first stage of the solidifying process bubbles are indeed formed, as appears, for instance, from the fact that the carbon content of the weld metal drops from 0.08-0.10% before welding to 0.06% after welding. The difference in carbon (in so far as it is not already oxidised during the melting of the electrode) must have escaped from the pool in the form of gaseous CO and CO_2. The initial formation of bubbles is also plausible for various other reasons. In the first place we have to bear in mind that C, O, H and N are much less soluble in solid iron than in liquid iron (cf. fig. 1), so that the growing crystals are continuously driving ahead C, O, H and N. In the layer of liquid immediately adjacent to the already solidified metal the concentrations of C, O, H and N will consequently not only be greater than those corresponding to the overall composition but even greater than those corresponding to the composition of the liquid outside this layer. In the second place it may be assumed that the contents not only of C but also of O, N and H in the liquid metal — which unfortunately are not known — are greater than those found in the solid iron after welding and which have been mentioned above. As far as hydrogen is concerned this can be derived from measurements taken by Mallett and Rieppel [10]), who found 42 vol. % hydrogen in the gases in the immediate vicinity of the arc when using an electrode corresponding to the Ph 50 type. To the partial pressure of 0.42 atm H_2, a dissolved quantity of 16 cm^3 per 100 gm of iron corresponds, but since the arc produces large quantities of atomic hydrogen, much more than 16 cm^3 H_2 per 100 gm will be absorbed by the liquid iron. Immediately after welding Mallett and Rieppel found no more than 15.5 cm^3 H_2 per 100 gm in the solidified metal. The difference must, at least for the greater part, have escaped from the metal in the form of gas bubbles while the metal was solidifying.

Going back to the picture we formed in the beginning of this article about the formation of holes due to gas bubbles, we may describe the situation when welding with electrodes of the Ph 50 type as follows: while the metal is solidifying there is some development of gas bubbles but under normal conditions this development ceases and the gas bubbles disappear before the outermost layer of the weld metal solidifies. By the time this takes place the concentrations of the dissolved gases have diminished to such an extent that the latent pressure no longer reaches the value required for the formation of gas bubbles.

The influence of sulphur

As an "abnormal condition" under which welds made with electrodes of the Ph 50 type *do* show porosity we mentioned in the beginning the presence of a relatively small quantity of sulphur in the iron to be welded. Can we now understand why there should be porosity in such a case?

Sulphur is practically insoluble in solid iron, so that crystals growing in liquid metal containing sulphur are continually driving the sulphur ahead. In other words, during solidification the layer of liquid immediately adjacent to the solid metal will contain an abnormally high concentration not only of C, O, H and N but also of sulphur. In the picture we formed above concerning the evolution of gas the gas nuclei are formed at the advancing solid-liquid interface. The bubbles probably develop from a small layer adsorbed on the wall, mainly on the sharp corners and edges of the growing crystals. We must now imagine that these favourable ("active") places for the formation of gas nuclei are blocked up by the sulphur, since this element is preferably adsorbed there. This "poisoning" of the interface causes the evolution of gas to be delayed: the bubbles are not formed until in a later stage of the solidification, when the supersaturation in the still liquid material has become so great that the formation of bubbles can no longer be prevented by the increase of the required latent pressure due to the lack of full cooperation of the poisoned interface. Thus this may lead to the formation of bubbles in the last stage of solidification, causing porosity. This would explain the sensitivity of the Ph 50 towards sulphur.

With type Ph 56 electrodes the situation is more favourable because, as appears from table I, the latent pressure of the dissolved gases is much lower. The supersaturation in the liquid metal remains so small that there is probably no formation of bubbles at all either at the beginning or at the end of the solidification, so that the presence of sulphur is not expected to have any effect.

It is probably due to the entire absence of bubbles that the Ph 56 electrodes lend themselves so well for overhead welding. The Ph 50 type of electrodes are not at all suitable for welding in this position, owing partly to the too low viscosity and surface tension of the metal deposited with that type of electrode, but probably also in part on account of the formation of bubbles at the beginning of freezing; the fact is that in overhead welding the bubbles are not able to rise and escape (fig. 6).

---

[10]) M. W. Mallett, Welding J. 25, 396S-399S, 1946; M. W. Mallett and P. J. Rieppel, Welding J. 25, 748S-759S, 1946.

The explanation given for the sensitivity of electrodes of the Ph 50 type for sulphur is supported by a number of experiments and many known facts, some of which will be mentioned.

Adsorption at "active" places on a surface of metal is also found in the phenomenon of heterogeneous catalysis. Now the action of sulphur in welding does not appear so strange when remembering that sulphur is known to be a catalyst poison. As far back as the first half of the last century it was known that the catalytic action of finely divided platinum upon the reaction between oxygen and hydrogen is eliminated by the addition of small quantities of sulphur compounds to the gas mixture. A more recent example is the dissociation of gaseous molybdenum carbonyl Mo $(CO)_6$ on hot surfaces 11). The layers of molybdenum obtained generally contain carbon owing to the dissociation of a part of the CO released. The precipitation of C can, however, for the greater part be avoided by adding a little H_2S to the carbonyl. This is probably caused by poisoning through the adsorption of sulphur on the active spots of the surface at which normally the dissociation of CO takes place. In welding, it is true, we are concerned with the formation of CO and not with its dissociation, but since a catalyst cannot change the position of an equilibrium the poisoning will delay both the formation and the dissociation of CO.

This phenomenon is likewise encountered in the manufacture of steel. Often silicon or aluminium is added to the liquid steel to "kill" it: the oxygen present is chemically bound and as a consequence the evolution of CO is prevented and the steel solidifies without gas bubbles being formed. Now it is known that sulphur also has a killing action: a quantity of 0.1% S is sufficient to suppress almost entirely the evolution of CO during the solidification 12). There is a very striking analogy with the effect of sulphur when welding.

We shall not go into various other cases here, some of which have been known for a long time, in which the formation of gas molecules (particularly of hydrogen) is prevented by catalyst poisons.

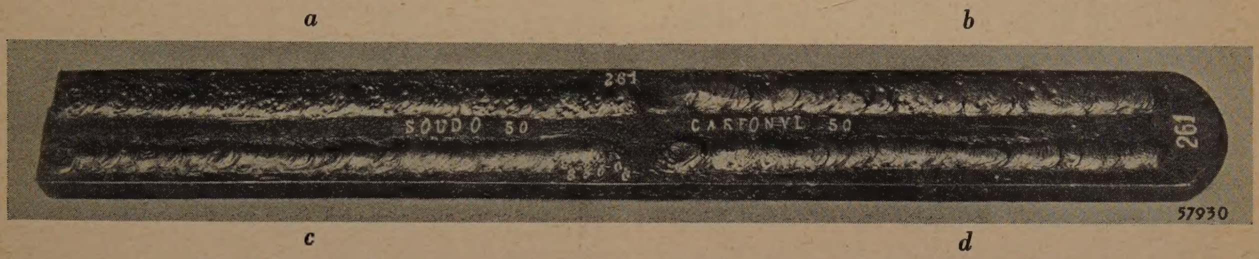


Fig. 7. Beads welded onto an iron plate free of carbon but containing 0.25% sulphur, *a*) with a mornal Ph 50 electrode; *b*) with a Ph 50 electrode the core of which contained no carbon; *c*) with a Ph 50 electrode from the coating of which the hydrogen had been expelled; *d*) with a Ph 50 electrode in which the conditions (*b*) and (*c*) were combined

The fact that the dissolved gases are responsible for the sulphur-sensitivity of the Ph 50 electrode is demonstrated in *fig.* 7, showing the result of welding tests on an iron plate free of carbon but with a high sulphur content (0.25%). Welding with a normal Ph 50 electrode, the iron core of which contains 0.1% C, gave the highly porous bead at the top left-hand side of the picture. With a carbon-free core the less porous bead at the top right-hand side was obtained. The fact that the latter bead still shows porosity is due to the presence of hydrogen. The two lowermost beads are much less porous and were obtained after heating two of the electrodes (with and without C in the core) for two hours in a stream of argon at 850 °C, the bound hydrogen being thereby driven out almost completely.

Welding under elevated pressure

In all the foregoing considerations the external pressure while welding has been assumed to be 1 atm. It is worth while considering what would happen if this pressure were greater than 1 atm.

The elevated pressure will have relatively little effect upon the amounts of gas taken up by the liquid metal: the nitrogen content of the metal deposited

---

11) J. J. Lander and L. H. Germer, Metals Technology 14, T.P. 2259, September 1947.

12) Second report on the heterogeneity of steel ingots, Iron and Steel Institute, London, 1928.

will certainly increase (proportional to the square root of the external pressure) but the oxygen content, which according to table I forms by far the most important source for any subsequent evolution of gas, depends mainly upon the composition of the electrode coating, or of the slag.

The latter is borne out i.a. by experience when welding with "Contact" electrodes. These form a longer cup and thus give a better protection to the depositing material against the influence of the atmosphere; the nitrogen content of the weld metal appears in fact to be less than that in welds made with the corresponding normal electrodes. However, one still finds the same oxygen content.

Assuming that the ideas developed in this article regarding the cause of porosity are correct, it may be expected that an increase of the external pressure might lead to the same result as the presence of sulphur, since it would make the formation of gas nuclei more difficult, whilst, as we have just seen, it does not cause any appreciable increase in the latent pressure available in the liquid metal. If the external pressure is very high it may even entirely prevent the formation of nuclei, as already stated. But if it is not too high the arresting of the formation of nuclei may result in the escape of gases being only delayed, possibly until the critical last stage is reached in the solidification, and in that case porosity is to be expected.

This effect has indeed been known for some ten years already as an experimental and hitherto unexplained fact: with electrodes of the Ph 50 type porous welds are obtained if the total external pressure amounts to say 2 or 3 atmospheres, as was experienced in the construction of the tunnel under the river Meuse at Rotterdam, where welding had to be done in the caissons under such a high pressure [13]).

In conclusion it seems advisible to recall what was said in the introduction to this article: an attempt was to be made to indicate a mechanism for the phenomenon of porosity in welds. The critical reader will have noticed that the picture developed is not in all details based upon exact data but rather upon plausible theories. The only justification for our considerations lies therefore in the fact that as yet nothing better seems to be available on the subject. We have formulated a working hypothesis; the quantitative development of the theory of the phenomenon may be a long and difficult task.

---

[13]) W. Gerritsen and F. G. van Riet, Smit-Lastijdschr. 3, 2-12, 1939. According to a verbal statement made by the firm of Smit, no porosity occurs when welding under elevated pressure with electrodes of the Ph 55 and Ph 56 types!

Summary. When welding with electrodes of the type Ph 50 the liquid metal unavoidably absorbs certain quantities of oxygen, hydrogen and also nitrogen. In the solidification of the metal (already containing carbon in solution) CO, CO_2, H_2, H_2O and N_2 are released in the form of gas bubbles. This liberation of gases from the metal, however, takes place, under normal conditions, before the outer layer solidifies. The "latent pressure" of the said gases in the metal is then, it is true, still greater than 1 atm (at least 2.27 atm, as found from a close consideration) but the formation of gas nuclei is prevented because, notwithstanding the cooperation of the "active places" of the interface between the solid and the liquid metal, this requires an additional pressure (capillary pressure); as a rule such a great latent pressure is no longer present at the end of the solidification, when most of the gas has already escaped. If there is any hindrance to the formation of gas nuclei, either through sulphur blocking the active places (poisoning) or in consequence of increased external pressure or through any other causes, then the formation of gas bubbles at the beginning of the solidification can be suppressed; it then takes place at the end of the solidification owing to the very much greater supersaturation. Such a "delayed" evolution of gas may account for porosity in a weld and in particular for the known sensitivity of electrodes of the Ph 50 type for sulphur. Also other facts, such as the insensitivity of the Ph 56 electrode to sulphur, fit well into the picture, but many other problems remain to be investigated further.

AN EASILY PORTABLE CATHODE-RAY OSCILLOGRAPH

by E. E. CARPENTIER.

621.317.755

For a number of years the cathode-ray oscillograph has been a widely known and indispensable instrument for the investigation of electrical phenomena (wave form, amplitude, frequency, phase shift, modulation, etc.). Much more interest has been taken in the oscillograph, however, since it came to be realized that mechanical and other non-electrical quantities can easily be converted into electric voltages. But the weight and dimensions of an oscillograph have often formed an obstacle to a wider use of this instrument. In this article the author explains how he designed an exceptionally small and light (and thus cheaper) apparatus which is eminently suitable for all sorts of routine and service jobs.

A few years ago there appeared in this journal a description of a cathode-ray oscillograph (type GM 3159) which was distinguished from older types by the fact that it contained two amplifiers, one for vertical and one for horizontal deflection 1)), thus making it more generally useful.

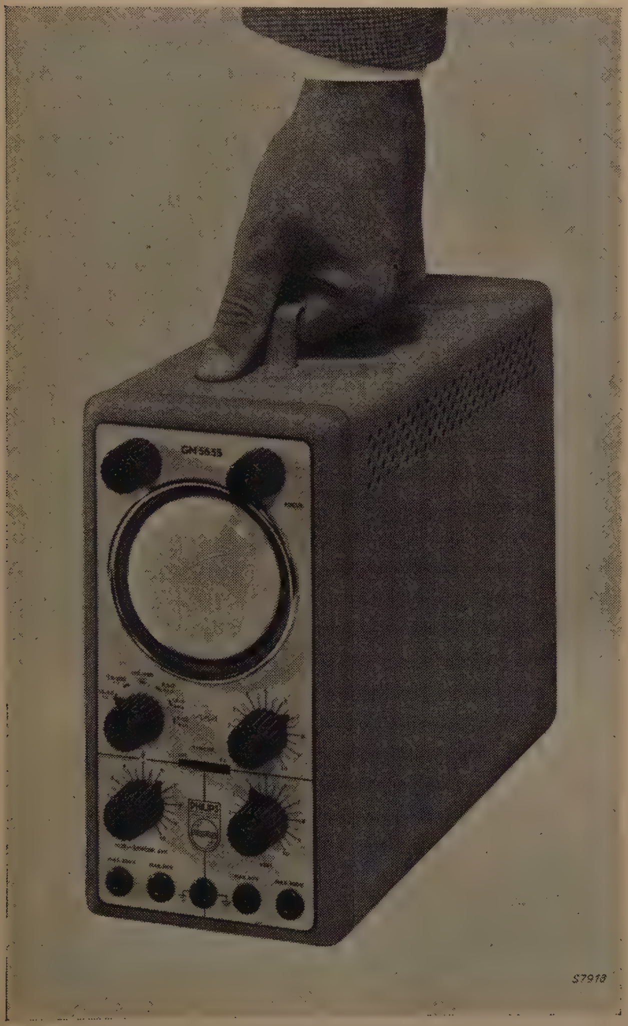


Fig. 1. Front panel of the small cathode-ray oscillograph GM 5655 (dimensions 11.5 cm × 29.5 cm × 24 cm or $4^{1}/_{2}'' \times 11^{1}/_{2}'' \times 9^{1}/_{2}''$, weight 6.4 kg or 14 lbs). At the top are the knobs for adjusting the intensity of the beam and for focusing. Below the screen of the cathode-ray tube: knobs for controlling the time-base frequency step by step and continuously, underneath these the input potentiometers for the two directions of deflection, and right at the bottom the terminal sockets. Over the Philips emblem is the "Intern."/"Extern." switch (see text).

Although this oscillograph was much smaller and lighter than its predecessors, the need was still felt for a type that could be more easily carried about. The fact is that an oscillograph has gradually become an indispensable instrument for maintenance work and for the tracing of defects in telephone communications, amplifying or radio installations, etc., and for such purposes easy portability is of great value.

To meet this need a new type of oscillograph (GM 5655) has been developed which will be described in this paper and compared in various respects with the type GM 3159 mentioned above. This small oscillograph, illustrated in *fig. 1*, has the following dimensions: width 11.5 cm, depth 29.5 cm, height 24 cm ($4^{1}/_{2}'' \times 11^{1}/_{2}'' \times 9^{1}/_{2}''$). It weighs 6.4 kg (14 lbs). Its volume (8.2 dm^3) is only 40 % and its weight 50 % of that of the GM 3159. *Fig. 2* gives a view of the inside of this apparatus.

Naturally it has not been possible to make such a drastic reduction in size without some sacrifice in performance compared with the type GM 3159, but it was not found necessary to make very great concessions — as will be shown farther on — and this small oscillograph will therefore also find a wide field of application.

General construction

Just like the GM 3159, this small oscillograph is fitted with a cathode-ray tube with a screen of 7 cm diameter, so that nothing has been sacrificed in picture size, and it has two amplifiers, the usual one for vertical deflection and another for horizontal

---

1) E. E. Carpentier, A cathode-ray oscillograph with two push-pull amplifiers, Philips Techn. Rev. 9, 202-210, 1947.

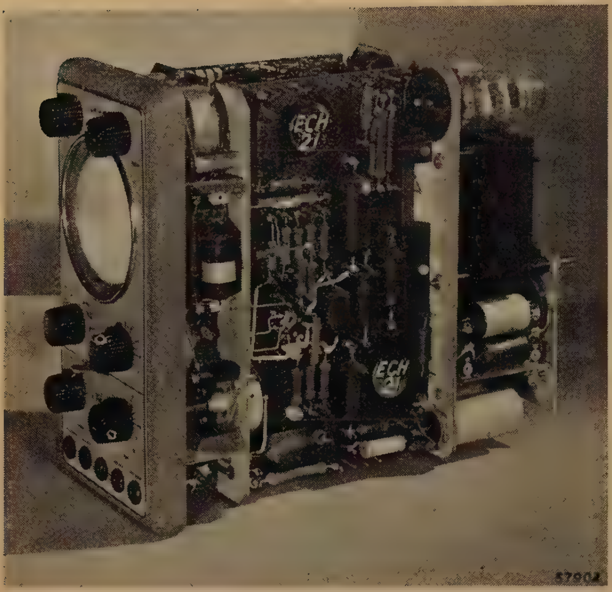


Fig. 2. The inside of the oscillograph GM 5655, showing two of the three ECH 21 valves and (on the right at the top) the two rectifying valves (EZ 2).

deflection. This second amplifier is often useful when studying a voltage as a function of some other arbitrary voltage (Lissajous figures); thanks to this second amplifier the latter voltage need have only a small amplitude to give quite a wide picture.

But this second amplifier also has its advantages for studying a voltage as a function of time, for the following reasons. If a reasonably linear saw-tooth voltage, required for the time base, is to be generated directly and with sufficient amplitude to give a picture of the full width allowed by the screen, this involves a rather complicated circuit. A saw-tooth voltage with sufficient linearity can, however, be generated in a very simple manner if its amplitude is small, but then an amplifier is needed to give it the amplitude desired. When such an amplifier is already to hand, as it is here, this method is by far preferable to the other.

As shown by the block diagram (*fig. 3*) of the GM 5655, an amplifier (A_v, A_h) is permanently connected to each pair of plates of the cathode-ray tube. When it is desired to study a particular voltage as a function of some other arbitrary voltage these voltages are applied to terminals *I* and *II* respectively and the switch S_1 is put in the position *1*. If, on the other hand, a voltage is to be studied as a function of time it is likewise applied to terminal *I* but S_1 must then be in the position *2*. Via the amplifier A_h the generator *TB* then supplies a saw-tooth voltage required to get a horizontal deflection proportional to the time. This saw-tooth voltage, the frequency of which is adjustable between wide limits, can be synchronized either with the voltage bringing about the vertical deflection or with some other arbitrary voltage. In the former case the switch S_2 has to be in the position "Intern.", synchronization then being brought about by the output voltage from A_v, whereas in the latter case S_2 is put in the position "Extern." and the synchronizing voltage is applied to the terminal *II*. Up to this point the arrangement of the oscillograph GM 5655 corresponds on broad lines to that of the larger type GM 3159.

It might be asked how it has been possible to reduce the dimensions and weight of this apparatus. Some concessions have had to be made as regards the quality of the picture and the frequency range for which the oscillograph is suitable, and from what follows it will be seen how by making such concessions it has been possible to reduce the volume and weight of this oscillograph.

Let us first consider the quality of the picture. Symmetrical control of the cathode-ray tube has been dispensed with in this small oscillograph. As a result some distortion takes place through focusing errors [2]) and the light spot is not equally sharp all over the screen. In the case of the type GM 3159 symmetrical control has been chosen because good picture quality is very valuable for certain measurements, but for a great many investigations focusing errors are permissible provided they do not occur to any great extent.

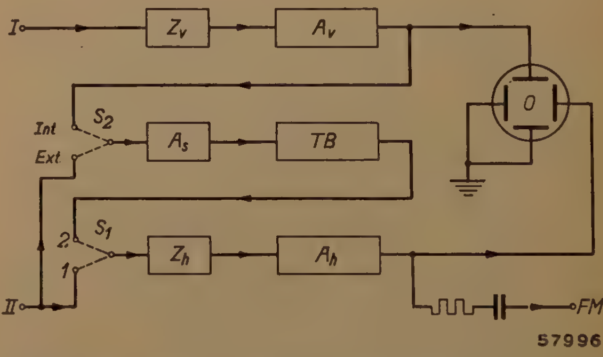


Fig. 3. Block diagram of the small oscillograph. *I*, *II* = input terminals, Z_v and A_v = attenuator and amplifier for vertical deflection, Z_h and A_h = ditto for horizontal deflection, *O* = cathode-ray tube, *TB* = time-base apparatus (saw-tooth generator), A_s = amplifier for the synchronization voltage, S_1, S_2 = switches, *FM* = connection for the frequency modulator GM 2881 (see the last paragraph of the text).

The advantage of asymmetrical control lies in the fact that it does not need a push-pull circuit, so that one valve can be saved in each amplifier. We shall now consider the amplifiers in more detail.

---

[2]) See Philips Techn. Rev. 4, 198-204, 1939, particularly figs. 3 and 4, page 199.

Amplifiers

With reference to the article quoted in footnote [1]), we would recall that the amplifiers of the oscillograph type GM 3159 each consist of a push-pull stage (without pre-amplification) which has to provide an amplification of 560 times to give the oscillograph the sensitivity required (corresponding to an input voltage of 25 mV R.M.S. per cm picture height). To maintain this high amplification factor in a wide frequency range it is necessary to have — as explained in the article referred to — a high supply voltage and a considerable supply current (675 V × 35 mA ≈ 24 W for the anodes and screen-grids of the four EF 50 valves together).

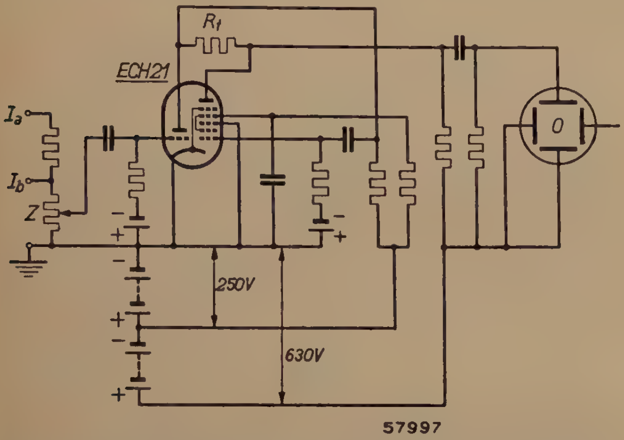


Fig. 4. Circuit diagram of the amplifiers of the oscillograph GM 5655. Each amplifier contains one ECH 21 valve. I_a = input for voltages up to 300 V, I_b = input for voltages up to 50 V, Z = input potentiometer, R_t = negative feedback resistor, O = cathode-ray tube (DG 7-2). The H.T. (250 V + 380 V) is supplied by two rectifiers in series, the negative grid biases are derived from a small selenium rectifier.

As regards the power a great saving has been reached in the amplifiers of the oscillograph GM 5655. Each of these consists of two stages (*fig.* 4) employing respectively a triode and a heptode which are incorporated in one bulb (ECH 21). The frequency range being limited to about 100 kc/s (in the case of the GM 3159 it extends to 500-1000 kc/s), only 4 mA is required in the output stage, with a supply voltage of 630 V. Owing to the smaller voltage amplitudes in the driver stage this stage needs no more than 250 V supply, again with a current of 4 mA. Thus the total D.C. power of all the amplifiers together amounts to 2 × (250 + 630) V × 4 mA ≈ 7 W, which is only 30 % of the corresponding power in the case of the GM 3159. This means a considerable saving in weight, not only of the mains transformer (the heaviest component of the oscillograph) but also of the chassis on which the transformer is mounted. The smaller size of the transformer and the saving of two valves and minor accessory parts result in a saving in volume, which in turn allows of a lighter cabinet. Obviously all this results in a lower price too.

If no negative feedback were applied the amplification of the first stage (triode) would be 12 times and that of the output stage (heptode) 400 times, thus making in all 4800 times. In order to get a flat frequency characteristic and a constant amplification whilst at the same time minimizing non-linear distortion, negative feedback has been applied which reduces the amplification to 500 times. With this amplification the sensitivity (corresponding to 30 mV per cm picture height) is hardly less than that of the oscillograph GM 3159. The negative feedback is brought about by means of a network represented in fig. 4 for the sake of simplicity as a resistor (R_t) but in reality having such a frequency-dependence as to improve the frequency characteristic of the amplifiers (*fig.* 5). Between 6 c/s and 100,000 c/s the amplification is within +5 % (0.4 db) and —25 % (—2.5 db) of the nominal value.

On the input side of each of the amplifiers there are two attenuators, one of which (Z, fig. 4) is continuously variable in the ratio 1 : 10,000 and can withstand 50 V, whilst the other, allowing the input voltage to be raised to 300 V, consists of a fixed resistor. For measuring phase relations the amplifiers can be used up to a frequency of 10,000 c/s when only the continuous attenuators are used, or to a frequency of 2500 c/s when the fixed attenuators are also in use; up to these limits the phase-shifts in the two amplifiers and the corresponding attenuators are equal and negligible.

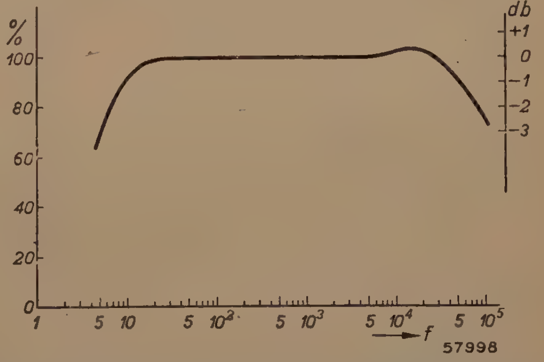


Fig. 5. Frequency characteristic of the amplifiers of the oscillograph GM 5655. The nominal amplification is taken as 100 %. On the right is a scale (in db) showing the deviation from this rating.

Time-base

The saw-tooth voltage for the time-base is generated in the same way as in the GM 3159, i.e. by a squegging oscillator. The valve used in this oscillator is of the same type as that employed in the amplifiers, an ECH 21, the heptode part of which is used for this purpose (*fig. 6*).

In connection with the afore-mentioned frequency range of the amplifiers the limits between which the time-base frequency is continuously adjustable have been chosen at 15 c/s and 20,000 c/s.

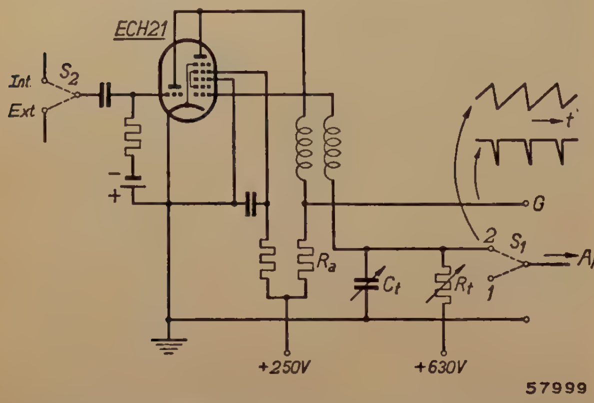


Fig. 6. Circuit diagram of the saw-tooth generator and the amplifier for the synchronizing voltage. The anode circuit of the heptode part of the ECH 21 valve is so tightly coupled to the grid circuit that a state of squegging arises. Periodically the grid capacitor C_t is thereby gradually charged through the resistor R_t and rapidly discharged across the grid. The saw-tooth voltage across C_t can be applied to the amplifier A_h. During the rapid discharge of C_t the valve oscillates for a moment, thereby taking up anode current and causing a sudden voltage drop in the resistor R_a. The voltage pulses thus obtained at the terminal *G* are used for blocking the electron beam in the cathode-ray tube during the flyback. The triode part of the ECH 21 valve serves as amplifier for the synchronizing voltage applied via the switch S_2 (cf. fig. 3).

A purpose has also been found for the triode part of the ECH 21 valve used in the time-base circuit: it serves as amplifier for the voltage with which the time-base can be synchronized [3]). As a result a smaller voltage suffices for synchronization than is required in the GM 3159, which lacks this amplifying stage.

During the flyback the electron beam in the cathode-ray tube is blocked, thus making the oscillogram clearer. As is the case with the GM 3159, this is brought about supplying to the control electrode of the cathode-ray tube during each flyback a negative voltage pulse derived from a resistor (R_a, fig. 6) in the anode circuit of the saw-tooth generator.

Use of the oscillograph at frequencies higher than 100 kc/s

Voltages with frequencies higher than 100 kc/s can also be investigated with this oscillograph provided they are amplitude modulated. In that case an auxiliary apparatus, the so-called measuring head GM 4575 (*fig. 7*), is needed for rectifying the voltage applied. This is useful for tracing defects in and testing radio sets, carrier telephony installations, etc.

So as not to be dependent upon some particular transmitter when taking such measurements of radio receivers, it is advisable to connect the aerial terminal of the receiver being tested to a service oscillator supplying a high-frequency voltage of variable amplitude and frequency. The modulation depth being known, the low-frequency voltage obtained after detection gives an indication of the value of the high-frequency voltage (without modulation).

The auxiliary apparatus referred to consists mainly of a small "Rimlock" pentode EF 41 acting as grid detector and contained in a case of "Philite". At one end this has a metal probe and at the other end a cable which has to be plugged into a socket at the back of the oscillograph. The necessary supply voltages are fed to the valve EF 41 via this cable, whilst its output voltage is connected to the vertical deflection amplifier. The circuit diagram is represented in *fig. 8*.

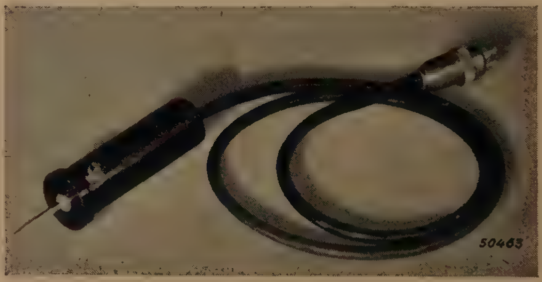


Fig. 7. Auxiliary apparatus (GM 4575) with which an oscillogram can be made of the audio-frequency voltage modulated upon a high-frequency voltage.

When the probe is connected in succession to, say, the input and the output of a certain h.f. or i.f. stage, with a suitably chosen sensitivity one can determine the amount of the amplification from the ratio of the amplitudes of the two oscillograms. A rough comparison of the amplitudes is often sufficient to localize a defect very quickly.

A switch on the measuring head allows a choice of two sensitivities corresponding to 65 and 650 mV (R.M.S. value) per cm picture height with a modulation depth of 30 %. Furthermore, the input potentiometer of the amplifier incorporated in the oscillograph is available for continuous adjustment of the sensitivity.

---

[3]) A description was recently given in this journal of a circuit in which the two systems of an ECH 21 valve are similarly used for a saw-tooth generator and for the synchronization of a saw-tooth voltage (see J. Haantjes and F. Kerkhof, Projection-television receiver, V. The synchronization, Philips Techn. Rev. **10**, 364-370, 1949, No. 12) but in which the functions of the triode and heptode parts were just the reverse of those in the present case. This is related to the fact that for separating television synchronization signals a multiple-grid valve is needed (as fully described in the article referred to). In the case of the oscillograph a reversal of the functions is more satisfactory.

The frequency range of the measuring head extends to about 30 Mc/s.

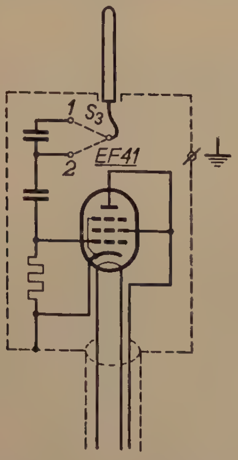


Fig. 8. Circuit diagram of the auxiliary apparutas GM 4575. The pentode EF 41 (connected as triode) serves as detector. S_3 = switch for low or high sensitivity (positions *1* or *2*).

Another purpose for which this small oscillograph can quite well be used in taking measurements on high-frequency apparatus is the recording of frequency characteristics (e.g. resonance curves). The manner in which this is done has already been explained at length in this journal [4]). All we need say here is that a high-frequency voltage modulated in frequency with the low-frequency saw-tooth voltage of the time-base of the oscillograph is applied to the receiver. This time-base is synchronized for instance with the mains frequency. The frequency modulator required (e.g. type GM 2881) has to be controlled by the saw-tooth voltage of the time-base. For this reason the oscillograph GM 5655 is provided with a connection (*FM*, fig. 3) from which this voltage can be taken off.

Summary. A description is given of an exceptionally small and light cathode-ray oscillograph (type GM 5655; 11.5 cm × 29.5 cm × 24 cm or $4^{1}/_{2}'' \times 11^{1}/_{2}'' \times 9^{1}/_{2}''$; 6.4 kg or 14 lbs). The small dimensions and light weight have been obtained by means of an asymmetrical control of the two pairs of deflecting plates of the cathode-ray tube and by limiting the frequency range for which the oscillograph is suitable to 100 kc/s. This has reduced the D.C. power required to only 3.5 W per amplifier. — The oscillograph contains two amplifiers, one for each direction of deflection. The horizontal deflection amplifier serves for amplifying either a saw-tooth voltage (as time-base) or some other arbitrary voltage (Lissajous figures). The two amplifiers are identical and each contains a triode-heptode ECH 21, with the two systems connected in cascade. For vertical deflection 30 mV (R.M.S. value) per cm picture height is required at the input. — In the time-base circuit (frequency 15 c/s to 20,000 c/s) an ECH 21 valve is likewise used, the heptode part of which is used for the saw-tooth generator whilst the triode part amplifies the synchronizing voltage. With the aid of an auxiliary apparatus (GM 4575) the amplitude modulation of a high-frequency voltage can be shown (for the testing of carrier telephony apparatus, radio sets, etc.). The oscillograph described is also suitable for recording frequency characteristics.

---

[4]) H. van Suchtelen, Application of cathode-ray tubes in mass production, Philips Techn. Rev. 4, 85-89, 1939.

CONSTRUCTION AND APPLICATIONS OF A NEW DESIGN OF THE PHILIPS VACUUM GAUGE

by F. M. PENNING and K. NIENHUIS

531.788.732

The Philips vacuum gauge, with which the pressure of a gas is measured by means of the intensity of a gas discharge in a magnetic field, was introduced 12 years ago and has now found application in many fields and proved to be a most useful instrument. Meanwhile the need has also been felt for such a simple vacuum gauge for measuring still lower gas pressures. This need has been met by changing the construction of the present gauge. In its new design this instrument is also quite useful as leak detector.

A description of the Philips vacuum gauge was given in this journal 12 years ago ¹). The tube used in this gauge contains two parallel plates of zirconium as cathode and a ring as anode (*fig. 1a*) and is placed between the poles of a permanent magnet with its field perpendicular to the cathode. Owing to the peculiar course of the electrical and magnetic lines of force inside the tube the electrons travel to and fro an immense number of times before reaching the anode, thus making many more collisions with gas molecules than would be the case if they travelled directly from the cathode to the anode. This large number of collisions can be interpreted as being derived from an apparent elevation of the gas pressure.

Consequently it is possible for a gas discharge to take place between cold electrodes at a pressure about 1000 times lower than is possible in a tube of a similar construction without magnetic field. It has been found experimentally that the magnitude of the discharge current is a good measure for the pressure.

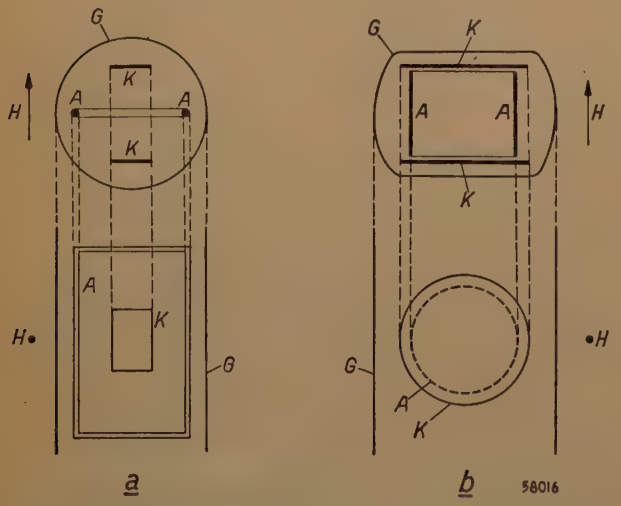


Fig. 1. Diagrammatic representation of the position of the cathode *K* and the anode *A* of the Philips vacuum gauge. *G* represents the glass envelope and *H* the direction of the magnetic field. *a*) The older design, *b*) the new design.

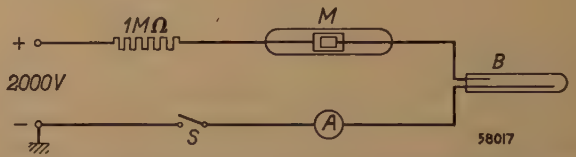


Fig. 2. The circuit diagram of the vacuum gauge *M* in series with the glow lamp *B*, acting as current indicator, and a micro-ammeter *A*. This circuit is applied both in the old design and in the new one.

This vacuum gauge, the circuit diagram of which is given in *fig. 2*, has in recent years been extensively applied in the manufacture of electronic valves and in apparatus in which the vacuum has to be maintained by means of a pump, as is the case with two kinds of apparatus previously described in this journal: the neutron generator ²) and the electron microscope ³). It can also be used, as described in literature on the subject, in combination with a "Pirani" manometer ⁴) or with a thermocouple manometer ⁵), in which case a larger pressure range is covered. Further, this instrument is very suitable for starting a certain signal ⁶) or activating a relay ⁴) ⁷) at the moment that the pressure exceeds a certain limit.

---

¹) F. M. Penning, High-vacuum gauges, Philips Techn. Rev. 2, 201-208, 1937.

²) F. A. Heyn and A. Bouwers, An apparatus for the transmutation of atomic nuclei, Philips Techn. Rev. 6, 46-53, 1941.

³) A. C. Dorsten, W. J. Oosterkamp and J. B. le Poole, An experimental electron microscope for 400 kilovolts, Philips Techn. Rev. 9, 193-201, 1947.

⁴) N. C. Picard, P. C. Smith and S. M. Zollers, A reliable high vacuum gauge and control system, Rev. sci. Instr. 17, 125-129, 1946.

⁵) R. I. Garrod and K. A. Gross, A combined thermocouple and cold-cathode vacuum gauge, J. sci. Instr. 25, 378-383, 1948.

⁶) R. S. Mackey, Non-linear indicator for vacuum gauge, Electronics, Febr. 1948, p. 140.

⁷) H. A. Thomas, T. W. Williams and J. A. Hipple, A mass spectrometer type of leak detector, Rev. sci. Instr. 17, 368-372, 1946; Detecting vacuum leaks electronically, Westinghouse Engineer, July 1946, p. 108.

For such applications the pressure range of 2×10^{-3} to 10^{-5} mm Hg covered by this vacuum gauge is generally sufficient, but in the manufacture of valves which are exceptionally sensitive to gas still lower pressures have to be measured.

The new vacuum gauge

The new vacuum gauge specially designed for lower pressures has a different electrode system (fig. 1*b*). The cathode plates are round discs parallel to the axis of the glass tube, whilst the anode is in the form of a cylindrical jacket perpendicular thereto. Where the cathode plates are mounted the glass tube is pinched. Thanks to this construction the same permanent magnet can be used with the new vacuum gauge as with the old one, whilst the electrical circuit (fig. 2) also remains exactly the same. *Fig. 3* is a photograph of the new gauge. Compared with the old one it has the advantage that the whole of the discharge space is enveloped by the electrodes and the discharge can no longer be affected by the glass wall and the thin layer of metal deposited upon it by sputtering of the cathode.

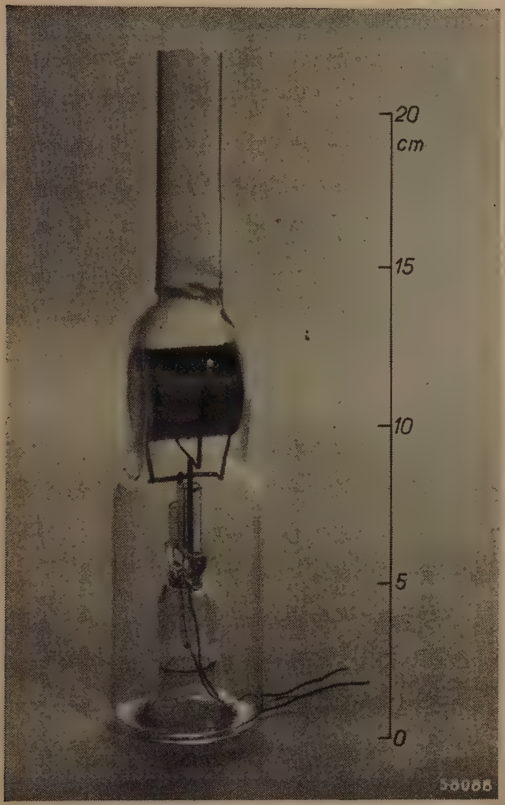


Fig. 3. Photograph of the new vacuum gauge.

In *fig. 4* the current flowing through the vacuum gauge has been plotted as a function of the gas pressure for the voltage (2000 V) and series resistance (1 megohm) usually applying also with the old type. This curve applies for air [8]), its trend depending more or less upon the nature of the gas. A comparison with the analogous curve (dotted line) for the old gauge (fig. 1*a*) shows that the sensitivity of the new vacuum gauge is about ten times greater, due, inter alia, to the larger effective surface area of the cathode. The curve for the new gauge has been drawn as a continuous line down to a pressure of about 10^{-6} mm Hg, but actually the discharge continues to take place at still lower pressures, in which range the sensitivity is represented approximately by the broken line; at such low pressures calibration is very difficult.

In the first description of the Philips vacuum gauge [9]) it was observed that when the pressure is reduced there is sometimes a sudden jump in the intensity of the current. With several specimens of the new design such a jump has been observed round about 10^{-4} mm Hg, thus at the upper limit of the pressure range. Below that pressure there were only small jumps.

Just as with the old construction, for currents between 10 and 1000 mA a small glowlamp (e.g. Philips 4662) can be used as indicator (see fig. 2),

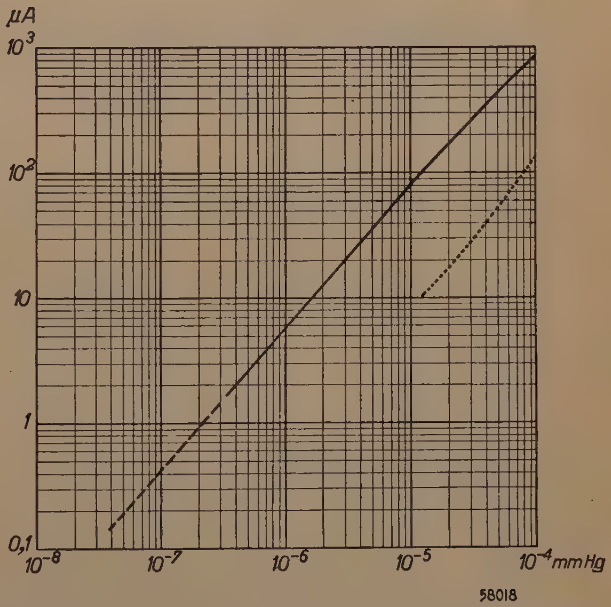


Fig. 4. The continuous line represents the current flowing through the new vacuum gauge plotted as a function of the gas pressure for the usual values of voltage and series resistance (2000 V, 1 megohm). The probable extension of the curve towards lower pressures is represented by the broken line; the dotted line relates to the old vacuum gauge.

---

[8]) The curve plotted is the average for three different tubes; the greatest deviation was 30 %.

[9]) F. M. Penning, Ein neues Manometer für niedrige Gasdrücke, insbesondere zwischen 10^{-3} und 10^{-5} mm, Physica, The Hague, 4, 71-75, 1937.

but for currents below 10 mA a more sensitive device is needed. A light-spot galvanometer with say 100 scale divisions for 1 μA is highly suitable for this purpose, one scale division corresponding to a difference in pressure of the order of 10^{-8} to 10^{-9} mm Hg. In order to get results at all reproducible in the range below 10^{-5} mm Hg it is of course necessary to degas carefully all glass walls and electrodes, including the vacuum gauge tube itself.

Leak detectors

In any pumping installation the vacuum gauge can also be used for detecting and tracing leaks. To find the origin of a leak in the object to be evacuated (for instance a transmitting valve or the pumping installation itself) one usually goes over the whole apparatus part for part, replacing the atmospheric air by some other substance. When the leak is reached this substance flows in and the gauge usually registers a change in pressure. As substitute one often uses a liquid, for instance water, and if the apparatus is fitted with a liquid air trap, in which the penetrating water vapour immediately condenses, the pressure in the apparatus will drop to a very low level.

The use of a liquid as substitute for air has its objections. It is not always possible to carry the liquid to the suspected places, and moreover the method becomes very cumbersome when some atmospheric air remains between the liquid and the leak and first has to be pumped away. It is therefore better to use instead of a liquid a gas which can be sprayed upon the suspected places. In recent years this principle has in fact been applied in various ways. For this reason we shall confine our further considerations to gases as substitutes for air. The usual method, whereby a leak is detected through a difference in the pressure registered by the vacuum gauge when the suspected place is sprayed, will be reverted to farther on, after we have first dealt with some other methods.

One can use as indication, for instance, the change in colour of a gas discharge. Hitherto this discharge has usually been brought about by means of a Tesla coil, but this requires a rather high pressure (at least 10^{-3} mm Hg). At lower pressures the change in colour of the discharge can be observed in the Philips vacuum gauge (old design) itself if the tube is provided with a window far enough removed from the discharge to be kept free from any sputtered material (see *fig. 5*). When a leak is sprayed for instance with hydrogen one can clearly see the discharge inside the vacuum gauge change colour.

For smaller leaks other methods have been devised 10), which were of great importance in nuclear research for testing the extensive vacuum apparatus required for separating U^{235} 11). For this purpose the apparatus was fitted with a mass spectrograph 7) sensitive especially to helium and the vacuum was tested by spraying with this gas. This method has the great advantage that helium can never occur as an impurity in the apparatus itself, such in contrast, for instance, to hydrogen. In most countries, however, helium is too expensive to be used for this purpose, whilst on the other hand the mass spectrograph is a rather complicated apparatus and the currents have to be amplified before being measured.

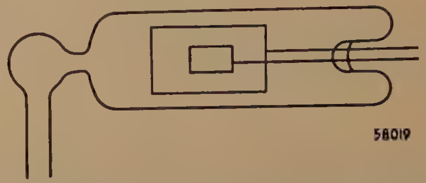


Fig. 5. A vacuum gauge (old design), used as leak detector, provided with a window through which the colour of the discharge can be seen to change when the leak is sprayed with some gas other than air.

Simpler in many respects is a method where advantage is taken of the fact that a heated wall of palladium is only permeable for hydrogen and not for air. With this method hydrogen has therefore to be used as substitute for air. The principle of the method is illustrated in *fig. 6*: the previously evacuated vacuum gauge *M* (e.g. an ionization vacuum gauge) is separated from the apparatus being tested by the palladium tube *P* which can be heated by means of the filament *F*;

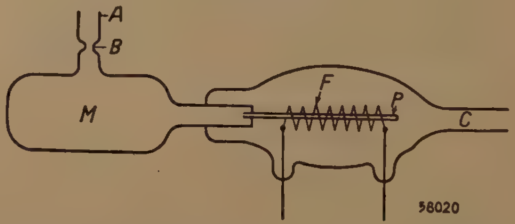


Fig. 6. Principle of a leak detector with palladium wall. *M* is the vacuum gauge which is evacuated via the tube *A*, sealed by fusing at *B* and then connected at *C* to the pump. *P* is the palladium tube which can be heated by means of the filament *F*.

---

10) For a more extensive review see the recent publication of S. Dushman, Scientific foundation of high vacuum technique, John Wiley and Sons, New York 1949.

11) R. B. Jacobs and H. F. Zuhr, New developments in vacuum engineering, J. appl. Phys. **18**, 34-48, 1947.

as soon as the jet of hydrogen strikes the leak hydrogen passes through P into M and raises the pressure.

The new vacuum gauge as leak detector

Owing to its high degree of sensitivity the new vacuum gauge described above is highly suitable for detecting small leaks. One can use, for instance, the arrangement shown in fig. 6, where M then represents the new gauge, which is first evacuated via the tube A and then sealed off at B, after which the whole device is connected at C to the pumping installation and the apparatus to be checked.

For tracing a leak the palladium tube is heated with the filament F and current is sent through the vacuum gauge. Since the discharge causes gas to disappear, after some time there will be a low equilibrium pressure, which is not zero because as a rule some hydrogen will still be passing through the heated palladium owing to hydrogen or hydrogen compounds being present in the pumping installation. To localize the leakage the pump is shut off by means of a cock and one goes over the outside of the apparatus with a jet of hydrogen in the manner described above. As soon as the current flowing through the vacuum gauge rises this gives an indication that the leak has been found. If there is any risk of an explosion a mixture of hydrogen with some other gas can be used, but then of course this reduces the sensitivity of the method.

Fig. 7 is an illustration of such a leak detector consisting of a vacuum gauge in the field of a permanent magnet and a bulb containing a palladium tube, the latter in this case being heated by the direct passage of current. The whole device is connected on the right-hand side to the apparatus being tested.

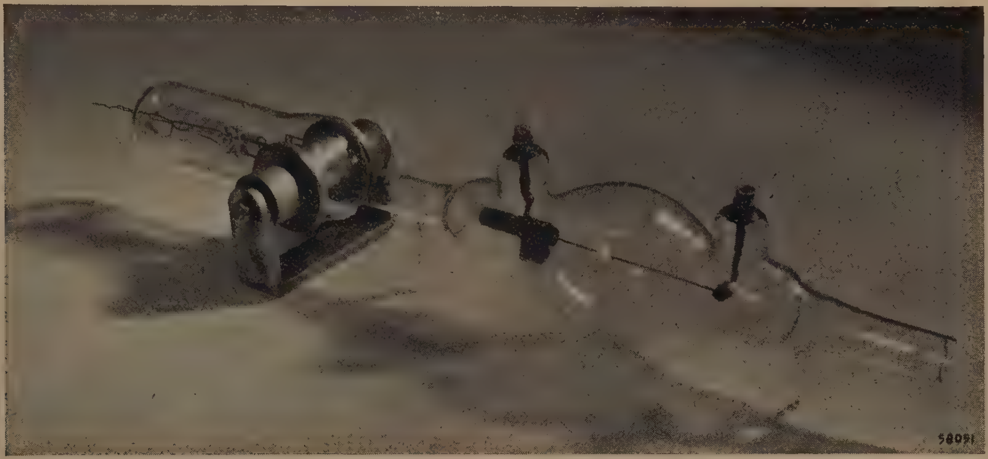


Fig. 7. The new vacuum gauge used as leak detector according to the principle of fig. 6. On the left the new gauge with magnet, on the right the envelope with the palladium tube heated by the direct flow of current via the contacts provided at the top of the envelope.

In *fig. 8* some examples are given of the variations in current as a function of time when a leak in an object (total volume about 2 litres) is exposed alternately to air and to hydrogen. The spraying with hydrogen begins where the arrow points upwards and ceases where the arrow points downwards. It is seen that the pressure continues to rise for some time after the spraying has been stopped. This is due to the fact that the leakage channel is still filled with hydrogen, the pressure ceasing to rise when all the hydrogen in this channel has been replaced by air and diffused through the pumping installation.

For these and subsequent measurements the leak was formed artificially by means of a very narrow glass capillary open to the outside air. Such a capillary is made by first reducing the diameter of the tube in a flame until the air channel inside is just visible, after which the tube is drawn out further and broken at its narrowest part. The leak can be enlarged by breaking off a piece of the capillary, and the tube can be sealed by holding the extremity in the flame for a moment. The passage is previously measured by allowing air to leak in for a considerable length of time. In this way it is possible to make capillaries passing through less than 10^{-7} $cm^3 \times$ mm Hg air per second.

The amount of hydrogen passing through the palladium depends upon the difference in pressure between the two spaces and thus upon the increase of the pressure in the object. For a given leak the sensitivity of this method is therefore roughly inversely proportional to the volume of the object.

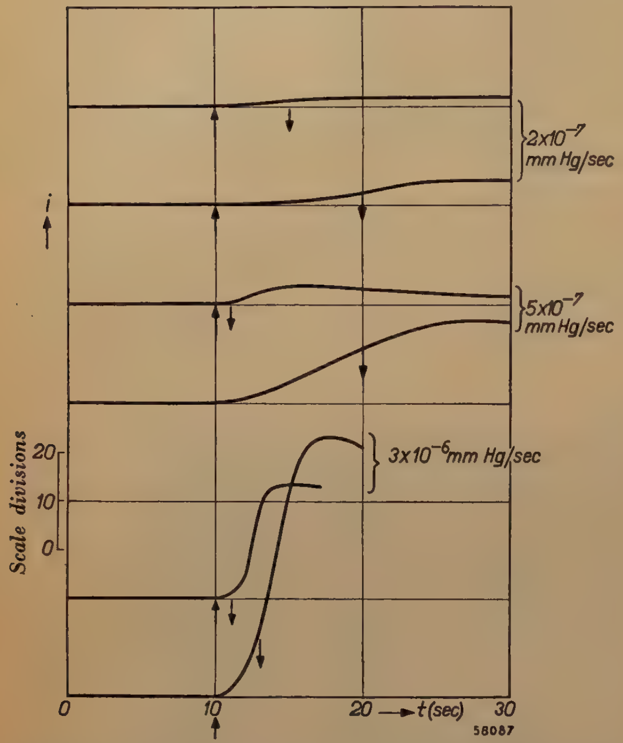


Fig. 8. Some examples of the current variation as function of time when a leak is alternately exposed to air and to hydrogen. Spraying with hydrogen begins at the arrow directed upwards and ceases at the arrow directed downwards. The initial current in air for $0 < t < 10$ sec is indicated at an arbitrary height above the t-axis. An idea of the sensitivity can be formed from the size of the scale divisions of the current meter given in the diagram. To the right of the curves the size of the leak in air is indicated in mm Hg per second.

As already stated, the principle of combining a heated palladium wall with an ionization vacuum gauge with hot cathode has been applied before [12]), the pressure being deduced from the ratio of the ion current to the electron current. The method described here is simpler because there is only one current to be measured and moreover this is greater than the non-amplified ion current in the other method. Another advantage is that when a leak is detected the hydrogen gas that has penetrated into the vacuum gauge can be more easily removed, so that one can pass over more quickly to the next test. In the method with a cold cathode the discharge itself will "burn away" the gas more quickly than when a hot cathode is used.

For the detection of still smaller leaks in valves which can be sealed off from the pumping device another method, without palladium tube, is to be preferred. A vacuum gauge is fused onto the valve to be tested and both of these are then evacuated as well as possible, after which they are sealed off from the pump (see for instance *fig. 9*). The current through the vacuum gauge is then switched on until it reaches a constant value. As already remarked, owing to the discharge a certain amount of gas disappears. In the state of equilibrium the amount burnt away per second by the discharge is obviously equal to the sum of that leaking in and that released from the walls, etc. If the amount of the gas released is negligible some idea of the size of the leak can already be formed from the current flowing through the gauge. On a former occasion [9]) it had been observed that in a well degased tube about 20 i cm^3 × mm Hg air per second is burnt away, i representing the current in amperes. In the case just assumed this is in fact the amount leaking in per second.

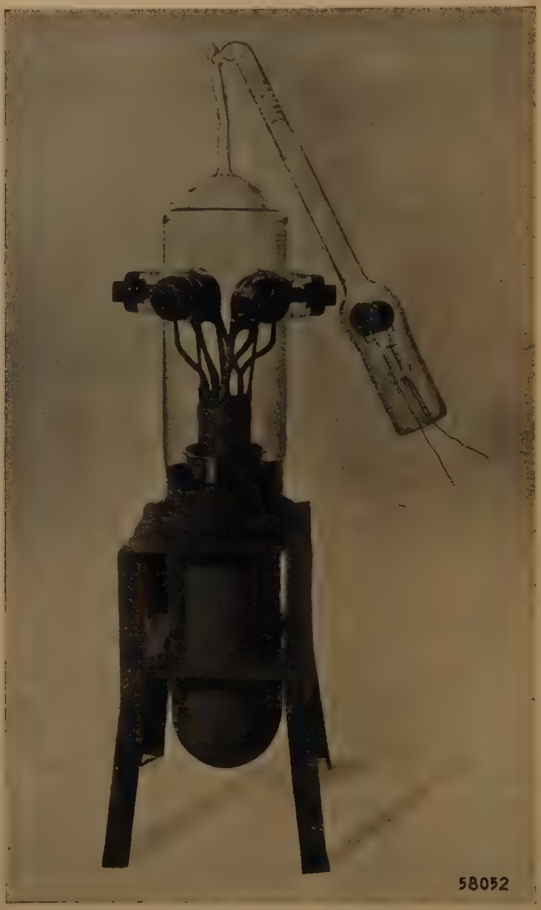


Fig. 9. Photograph of a transmitting valve with vacuum gauge fused on, by which means a leak was found in one of the metal caps for the current lead-ins.

In order to localize the leak one can now spray the valve to be tested with some gas other than air.

---

[12]) H. Nelson, The hydrogen gauge, an ultrasensitive device for location of air leaks in vacuum-device envelopes, Rev. sci. Instr. **16**, 273-275, 1945.

The current passing through the gauge will generally depend upon the nature of the gas used, because both the rate at which the gas leaks in and that at which the burning away takes place are related thereto, whilst the sensitivity of the instrument also depends upon the kind of gas. Good results have been reached for instance with argon and hydrogen as substitutes. *Fig. 10a* gives some examples of the results obtained with argon. The leak was again in the form of a capillary shaped as described above, and this was directly fused onto the vacuum gauge as indicated in fig. 10*b*. Just as in fig. 8, the arrows indicate the beginning and the end of the spraying of the leak with the gas. When spraying for only one second the current returns to its initial value within a few seconds owing to the argon being burnt away. When spraying for 10 seconds (curves and arrows drawn in dotted lines) the current reaches within a few seconds a new state of equilibrium whereby just as much argon is burnt away as flows in.

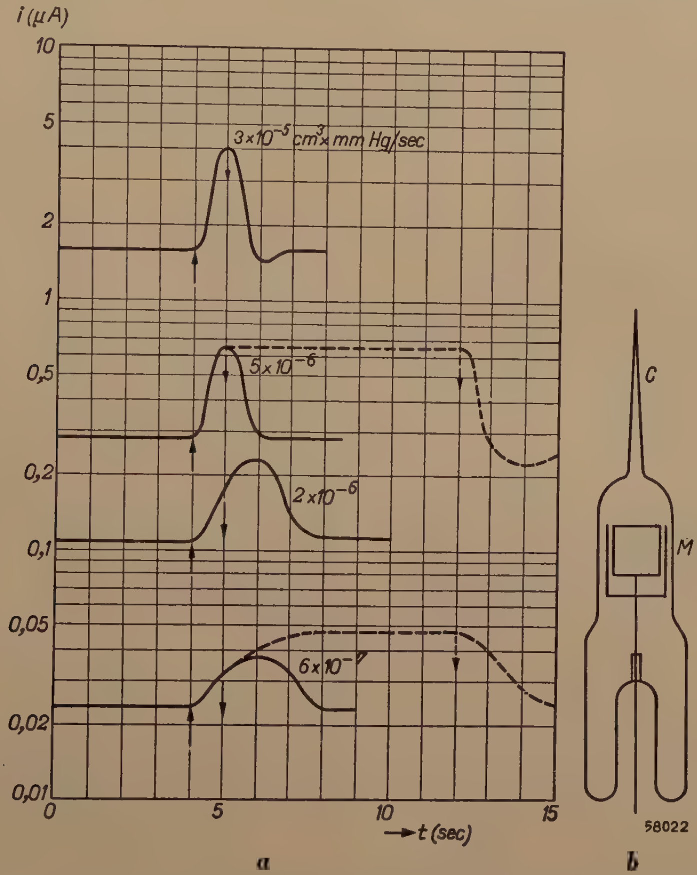


Fig. 10. *a*) Some examples of the detection of leaks in a valve evacuated with the vacuum gauge to which it was fused (the substitute gas was argon). The size of the leak is indicated at the right of the curves in cm³ × mm Hg per second. When no more gas is released from the glass wall and the electrodes then the value at which the current through the gauge reaches an equilibrium, with air around the tube, ($t<4$ sec in the diagram) already gives an idea of the extent of the leakage. *b*) illustrates the manner in which the artificial leak in the form of a capillary *C* was connected to the vacuum gauge.

In this way it is possible to determine extremely small leaks of about 2×10^{-7} cm³ × mm Hg/sec, corresponding to an increase in pressure in the volume of the manometer of 0.0025 mm per month. The sensitivity is several hundred times greater than that given for the mass spectrograph method. An advantage of the latter method, however, is that the inflowing helium can also be measured when there is already a fairly high pressure of other gases in the apparatus. Moreover, to reach the maximum sensitivity with the method described here it is essential that both the object being tested and the manometer together must be well degased, so that the residual pressure is determined only by the leakage.

In most cases the valves to be tested will have a volume of the same order of size or greater than that of the tube of the vacuum gauge, in which case it will take longer for the air to be replaced by the gas injected. *Fig. 11a* gives an example where there is a volume of about 1 litre between the leakage capillary and the vacuum gauge (see also fig. 11*b*). For the same size of leak both the initial value before spraying and the ultimate value after spraying will be the same as in the case of fig. 10. In both cases when the state of equilibrium is reached the amount of gas burnt away by the discharge equals the amount flowing in through the leak. When, however, a volume of 1 litre is placed in between the vacuum gauge and the capillary the transition from the initial value to the ultimate value takes place much more slowly. This may be seen when comparing fig. 11*a* with fig. 10*a*. In fig. 11*a* it has moreover been indicated by a dotted line what increase in current might be expected if the volume of 1 litre were omitted. With larger volumes it thus takes much longer to detect a leak, but apart from this the sensitivity is just as great as in the case of smaller volumes.

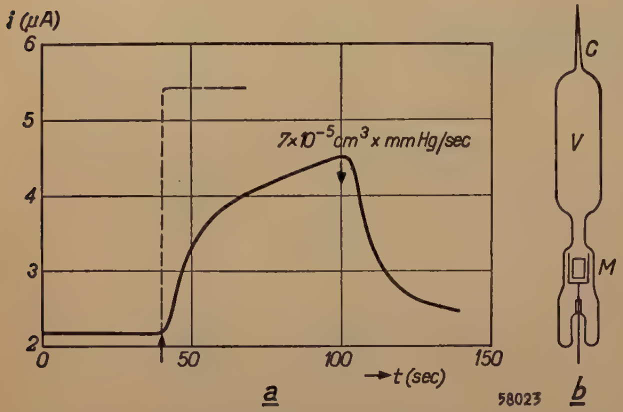


Fig. 11. *a*) An experiment similar to that in fig. 10 but with a volume *V* of 1 litre between the vacuum gauge and the capillary. The broken line shows the trend to be expected for this leak if the capillary were attached in the manner indicated in fig. 10*b*. *b*) The manner in which the artificial leak (capillary *C*) was affixed to the vacuum gauge.

Summary. The Philips vacuum gauge previously described in this journal is suitable for gas pressures of 2×10^{-3} to 10^{-5} mm Hg. In order to produce a vacuum gauge based upon the same principle but useful for lower pressures, the electrode system has been replaced by another consisting of two parallel round metal discs as cathode and an anode in the form of a cylindrical jacket. To keep the distance between the pole shoes of the permanent magnet enveloping the glass tube as short as possible this tube has been pinched at that point. These improvements have given the new instrument a sensitivity about ten times as great: it covers a range from 10^{-4} to 10^{-6} mm Hg and can probably be used for pressures even below 10^{-7} mm Hg. Vacuum gauges are also used as leak detectors and some methods followed for this purpose are briefly discussed. It is indicated how the new design of vacuum gauges can best be employed for such an application.

HEATING THE FILAMENTS OF VALVES IN A CASCADE GENERATOR BY MEANS OF HIGH-FREQUENCY CURRENT

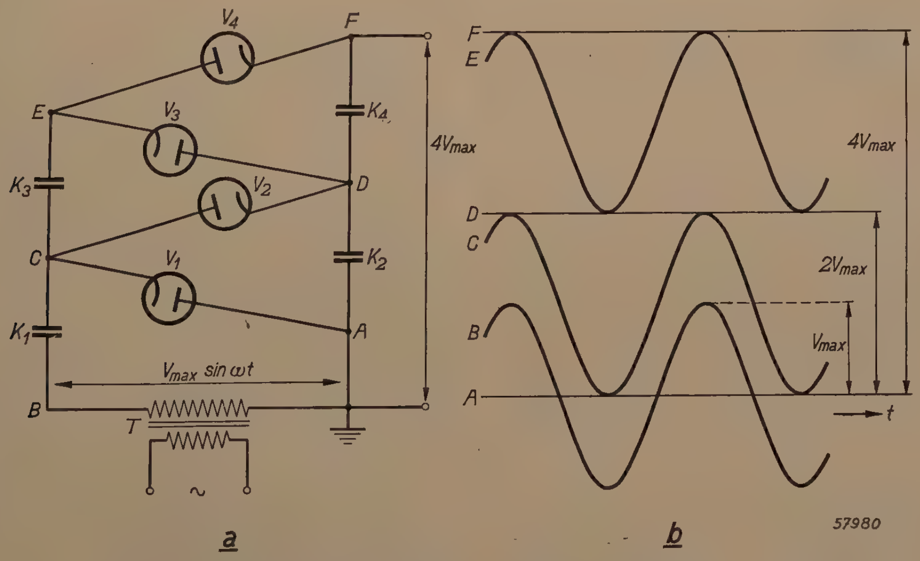
by Tj. DOUMA and H. P. J. BREKOO.

621.314.671:621.3.032.44:621.3.023

In a cascade generator the filaments of the valves are at a very high potential with respect to earth. The difficult problem of how to heat these filaments has in principle been ingeniously solved by employing high-frequency current. In the practical application of this method, however, difficulties were encountered which involved the use of highly complicated circuits. Thus in a cascade generator with 12 valves no fewer than 15 tuned circuits were needed. Partly due to the use of "Ferroxcube" for the filament-current transformers it has now been found possible to simplify the circuits appreciably.

A very high D.C. voltage is needed both for generating X-rays and in nuclear physics. For the supplying of such a voltage in the order of 10^5 to 10^6 V for instance, the cascade generator is highly suitable. The circuit of such a generator has been described several times in this journal [1]), so that it will suffice here to give a brief explanation in the caption of *fig. 1* representing the basic circuit.

In the designing of a cascade generator one of the problems is how to apply the power required for heating the cathodes of the valves. The most obvious method is to supply each valve from its own transformer connected to the mains. In the case of installations for very high tensions however great difficulties are encountered in insulating the two windings of the transformers from each other particularly in those supplying the uppermost valves (uppermost both in the drawing and in actual execution), which are at the highest potential with respect to earth.



a b

Fig. 1. *a*) Circuit diagram of a cascade generator with four valves ($V_1 \dots V_4$) and four capacitors ($K_1 \dots K_4$). T = transformer; peak value of secondary voltage = $V_{\max}$. The potential at the points $B \dots F$ with respect to the earthed point A has been plotted in (*b*) as a function of the time t, with the corresponding lettering. This diagram applies for no load. It is readily seen that the ratio of the highest D.C. voltage obtained (between F and A) to $V_{\max}$ equals the number of valves (in this case four).

Right from the beginning other means have therefore been sought. At first each filament was fed from its own insulated accumulator, later on from a separate dynamo, the dynamos being driven by a single motor by means of long insulating shafts. These solutions, however, were far from ideal.

---

[1]) A modern high-voltage equipment, Philips Techn. Rev. **1**, 6-10, 1936; A. Kunkte, A generator for very high direct current voltage, Philips Techn. Rev. **2**, 161-164, 1937. Sometimes the cascade generator renders good service also for lower voltages, see for instance G. J. Siezen and F. Kerkhof, Projection-television receiver, III. The 25 kV anode voltage supply unit, Philips Techn. Rev. **10**, 125-134, 1948 (No. 5), in which article a further analysis of the working is to be found for a particular case.

Feeding with high-frequency current

It was a big step forward in the right direction when Kuntke evolved the idea of feeding the filaments with a high-frequency current passing through the filaments connected in series via the capacitors of the cascade system itself (see the first of the articles quoted in footnote [1]). The principle of this method is represented in *fig. 2.*

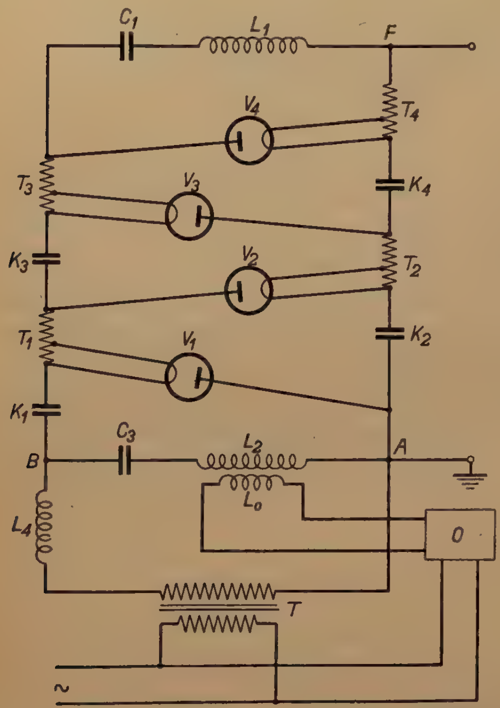


Fig. 2. The filaments of the valves are fed via autotransformers $T_1 \dots T_4$ with a high-frequency current generated by the oscillator O and circulating through the circuit L_2-C_3-K_1-T_1-K_3-T_3-C_1-L_1-T_4-K_4-T_2-K_2-L_2. The capacitors $K_1 \dots K_4$ have a negligible impedance to high frequencies, whilst C_1-L_1 by-passes the uppermost valve, and the choke L_4 blocks the path through the transformer T. The capacitor C_3 prevents L_2 and L_4 from forming a short-circuit across T.

This figure likewise shows that filament-current transformers are still employed in this method, since the filament-current itself (3.5 A for a frequently used type of valve) is too high to be circulated without considerable loss. These transformers, however, have the primary winding connected to the secondary, so that here the difficulty of insulation does not arise. At first transformers were used with a ratio of 5:1, so that the primary current amounted to 0.7 A. This current was generated by a valve oscillator working at a frequency between 500 and 750 kc/s.

Attention is drawn to the capacitor C_3 (fig. 2), which prevents the coil L_2 of the h.f. transformer from forming a short circuit for the secondary current (mains frequency) of the main transformer T; further attention is drawn to the choke L_4 preventing the flow of h.f. current through T. There is also a circuit C_1-L_1 tuned approximately to the oscillator frequency and thus providing an h.f. by-passing for the uppermost valve, whilst blocking the direct current.

Objections to the original system

This solution of the problem of heating the filaments, so ingenious in principle, is in practice not so simple as it appears.

The junction points B, C, $D \dots$ (fig. 1) of a cascade generator are at a high potential with respect to earth. In order to avoid corona discharge it is necessary to enclose each of these points in a rounded metal envelope which is connected to the junction point (*fig. 3*) and which, when viewed from the outside, may nowhere have too small a radius of curvature. In particular the large envelope of the high-voltage equipotential surface — the "hood" — is worthy of note (see *fig. 4*).

Each of these envelopes has a certain capacitance with respect to earth (sometimes almost as much as 100 pF). These capacitances present considerable shunt paths to high frequencies. As a result the filament currents of the valves are not equal and therefore each valve is not fed with the current most favourable for long life.

With a view to equalizing the filament currents as far as possible two steps have been taken to reduce the high-frequency potential of the envelopes, so as to minimize the leakage of current.

The first of these steps consists in tuning each filament circuit to the oscillator frequency with the aid of a series capacitor; this circuit has a quite considerable self-inductance — consisting for the greater part of the stray self-inductance of the filament-current transformer — in which there is a considerable voltage drop. By tuning the circuit this is compensated and as a result the primary potentials, and thus

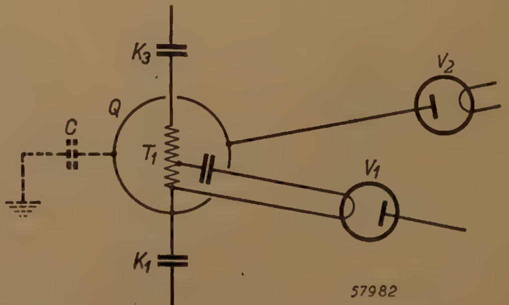


Fig. 3. To avoid corona discharges each of the junction points of the cascade generator which are at a high potential (B and the transformers T_1, $T_2 \dots$ in fig. 2) is surrounded by a rounded metal envelope Q, as represented here for T_1. These envelopes have a capacitance C to earth which by-passes a portion of the H.F. current.

also the h.f. voltages on the envelopes, are considerably reduced.

The second step consists in the application of a kind of bridge circuit, the principle of which is represented in *fig. 5*. By this means the high-frequency potential of the "hood" with respect to earth can be reduced to zero. It is true that the lower junction point envelopes then have a greater h.f. potential than is the case in the asymmetrical system shown in fig. 2, but this is outweighed by the fact that there is no longer a leakage current from the large hood.

Attention is also drawn to the circuit L_3-C_3 required in this system. The high-frequency current to which it is tuned can easily pass this circuit. The capacitor C_3 serves to block the direct current. C_2 is a variable air capacitor which has to be adjusted when the coupling between L_2 and L_0 is changed.

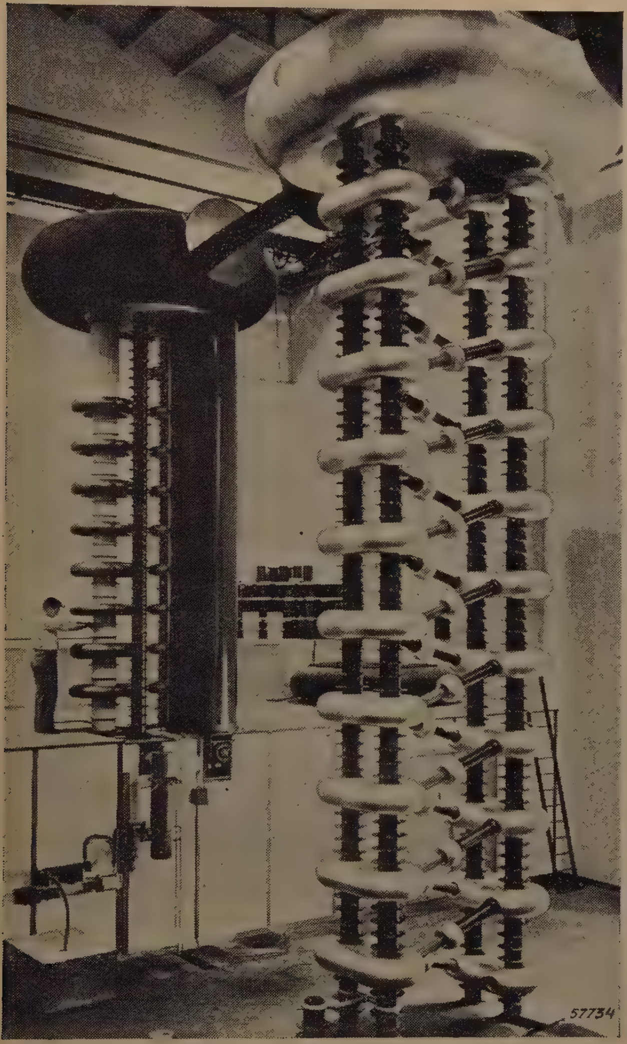


Fig. 4. A 2000 kV cascade generator (on the right) installed in the Cavendish Laboratory at Cambridge (England). It has twenty valves. The geometrical construction corresponds to the form in which the diagram of fig. 2 has been drawn. This installation is connected to a tube (on the left) in which nuclear reactions are brought about. Note the rounded corona shields of the junction points and the large "hood" forming the non-earthed D.C. terminal. The capacitance of these parts causes an unequal distribution of the h.f. filament current of the valves.

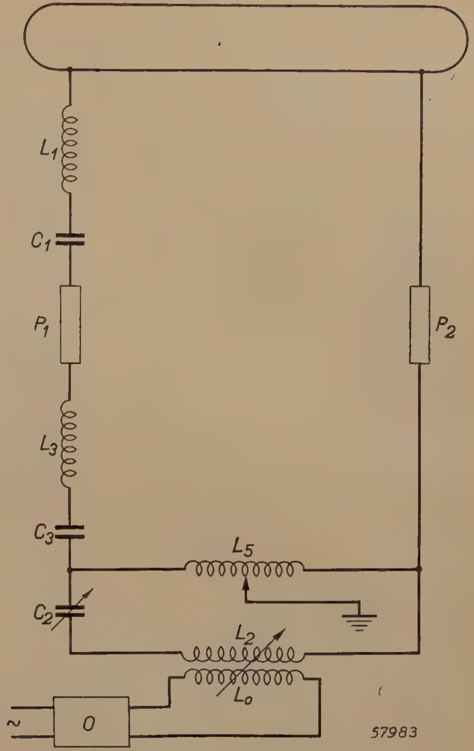


Fig. 5. A circuit allowing the h.f. potential of the "hood" *H* to be reduced to zero, by means of adjustment of the tapping on the coil L_5. The parts carrying only low-frequency current have been omitted. P_1 and P_2 denote the two columns. The capacitor C_3 is necessary to insulate the bottom of P_1 from earth for direct voltage; the coil L_3 compensates the high-frequency impedance of C_3. The circuit is tuned by means of the variable capacitor C_2. The other letters have the same meaning as in fig. 2.

It will be readily understood that these measures cannot be said to simplify the installation. This is demonstrated most clearly by the diagram in *fig. 6* representing the system of cascade generators actually constructed. In this system with 12 valves (with which a D.C. voltage of more than 1000 kV can be obtained) there are no fewer than 15 circuits to be tuned: the 12 filament circuits plus the circuits L_1-C_1, L_2-C_2 and L_3-C_3. Moreover, there is the variable coupling L_0-L_2 and the tapping of L_5. Needless to say, it is no easy matter to adjust all these elements in such a way that the twelve filament currents are kept within certain limits. It is true that, in theory, this adjustment has only to be made once for all, but it does not take much to disturb the balance for proper functioning.

Added to this is the fact that the losses in the two columns (mainly in the high-tension capacitors C_1 and C_3) with a high-frequency current of 0.7 A may be of the same order as the power consumed by the filaments. Thus the efficiency is not favourable.

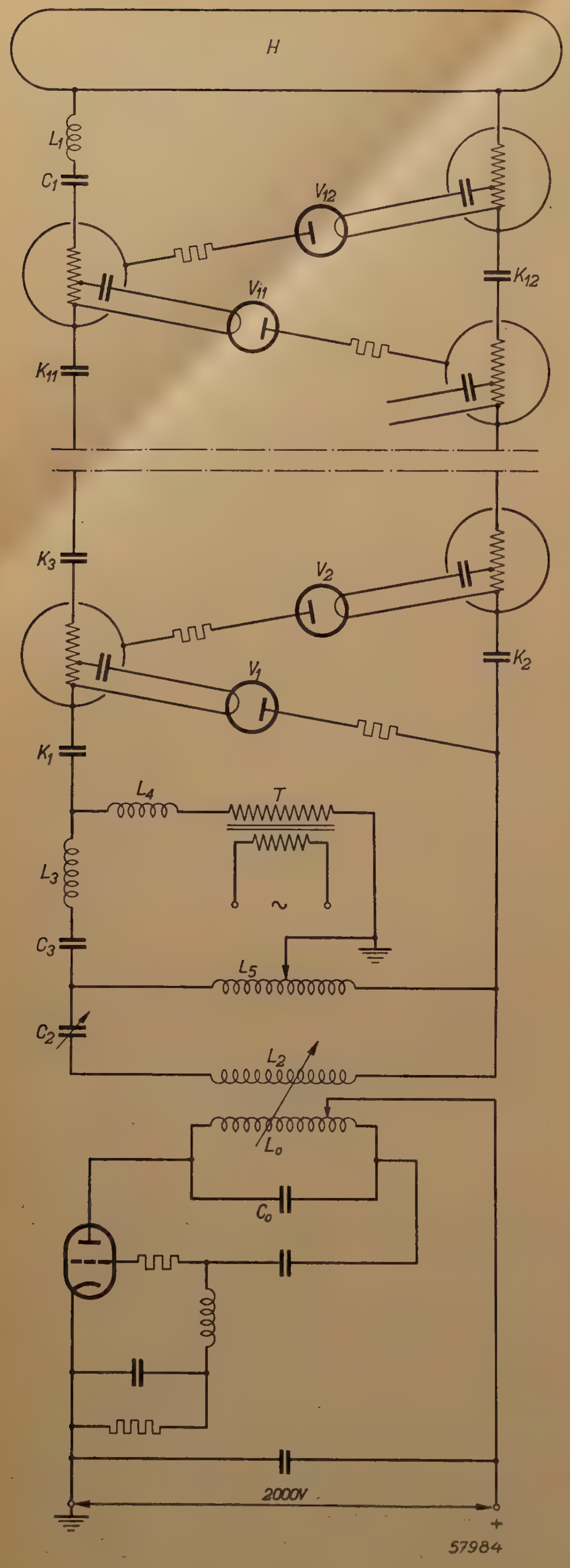


Fig. 6. Superseded circuiting diagram of a cascade generator with h.f. filament heating (12 valves). To compensate inductive voltage drop each filament circuit is tuned with a series capacitor. The circuit is symmetrical (coil L_5, cf. fig. 5). L_0-C_0 = oscillator circuit. The other letters have the same meaning as in fig. 5. Connected in series with each valve is a resistor for limiting current surges which might occur when switching on.

The new system

A new system has been devised which is much simpler, mainly because the tuning of each filament circuit has been dispensed with. Moreover, the losses have been reduced, partly due to the use of a smaller primary current (0.25 A instead of 0.7 A).

These two measures together result in the first place in a higher primary voltage per filament current transformer. This, as we have seen, is undesirable on account of the capacitive leakage currents, which moreover become more important with a primary current of 0.25 A than with one of 0.7 A. This objection has been adequately overcome by adopting two further measures.

In the first place a lower frequency has been chosen, thereby reducing the h.f. voltage drops in the secondary circuit of each filament current transformer. Taking into account the need to be able to introduce the new system into existing installations with as little alteration as possible, we found the most favourable frequency to be approximately 250 kc/s (as mentioned previously, the frequency was 500 to 750 kc/s).

The second measure consists of a drastic reduction of the magnetic leakage of the filament current transformers, which are responsible for a large part of the self-inductance in the secondary circuit. This has been achieved by using a core of “Ferroxcube” 2) for the transformer instead of one made of iron dust mixed with “Philite” as previously used. This new material has very low magnetic losses (also at high frequencies) and a high permeability (in the order of 1000). The parts from which the core is built up, two E-shaped pieces (see *fig. 7*), can easily be ground so smooth that no appreciable air gap remains in the path of the lines of force. It is due to these two properties of the material that the magnetic leakage of the transformer is so small. This renders the tuning of the filament circuits superfluous.

Fig. 8 shows two complete transformers, one detached and one mounted on the bracket which also carries the valve socket.

The winding ratio is 14:1, corresponding to a primary current of 0.25 A. The loss in the capacitors C_1 and C_3 (fig. 6) is much smaller than the power consumed by the twelve filaments together.

The complete circuit diagram is shown in *fig. 9*. It is also to be seen that the oscillator circuit has been simplified (cf. fig. 6) and that a bridge circuit, making the high-frequency potential of the hood zero, is no longer used. It has been found that,

---

2) J. L. Snoek, Non-metallic magnetic material for high frequencies, Philips Techn. Rev. 8, 353-360, 1946.

thanks to the simplifications introduced, the irregularities in the distribution of current can be made so small, even with an asymmetrical circuit, that a slight correction to each filament current transformer is sufficient to confine the current intensities within the fixed limits. This applies even to the large number of twenty valves as contained in the installation illustrated in fig. 4. If desired, however, the circuit can be made symmetrical (*fig. 10*), in which case, under favourable circumstances, even the individual corrections are unnecessary.

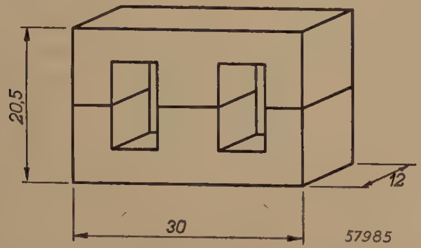


Fig. 7. The new filament-current tranformers have a core consisting of two solid E-shaped pieces of "Ferroxcube", drawn here to actual size; dimensions are in millimeters.

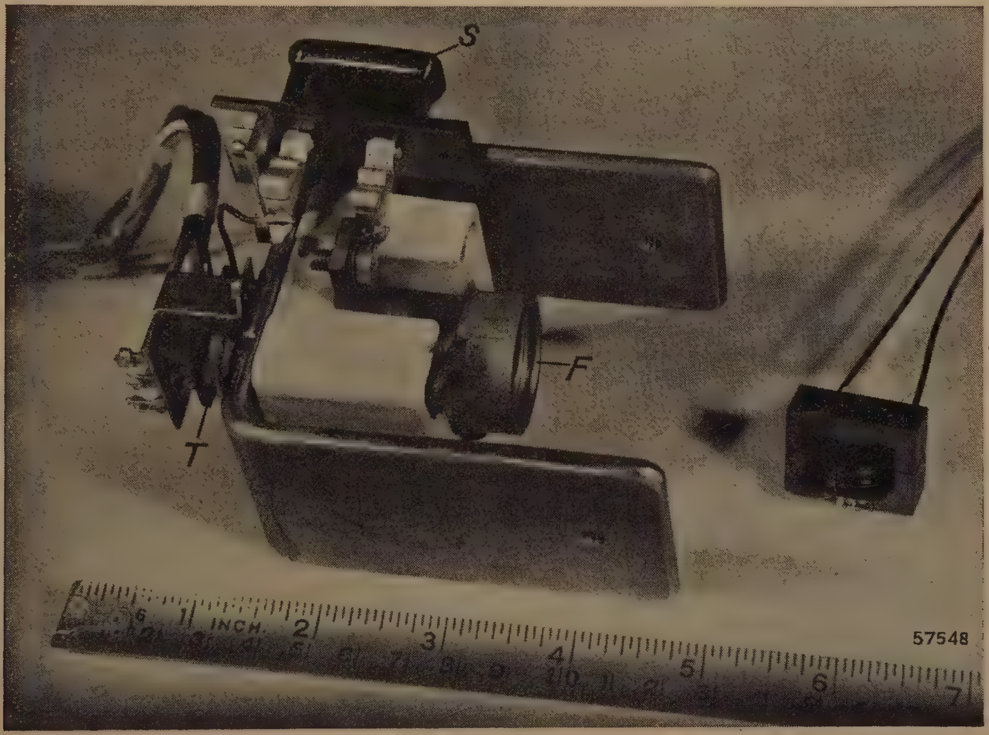


Fig. 8. *Right:* A complete transformer for a secondary power of 2.3 V × 3.5 A = 8 W, frequency 250 kc/s. *Left:* Bracket on which are mounted the filament current transformer *T*, the valve socket *F* and a plug socket with short-circuiting plug *S* which can be replaced by an ammeter for the purpose of checking.

Adjustment

From fig. 9 it is to be seen that the tuning capacitor and the grid resistor of the oscillator can be adjusted. By this means the optimum frequency can be chosen and the output varied by about 10%.

Before the installation is put into use it is necessary to check once for all whether the filament currents are within the fixed tolerances. For this purpose there is a socket at each valve which is normally short-circuited (fig. 8) but to which an ammeter can be connected for testing.

Experience has shown that in the new installation all valves receive approximately the correct filament current if that of the two lowermost valves (to the high-frequency current these are the first and last valves) has been adjusted to the correct value; see *fig. 11*. If necessary any remaining small deviations can be corrected, for instance, by using tappings on the primary winding of the filament current transformers. The mean level of the filament currents — which in fig. 11, curve *c*, is still slightly too high — can be adjusted to the desired value with the aid of the oscillator grid resistor.

Another great practical advantage of this new system is that, thanks to its simplicity, once it has been adjusted it does not easily become detuned.

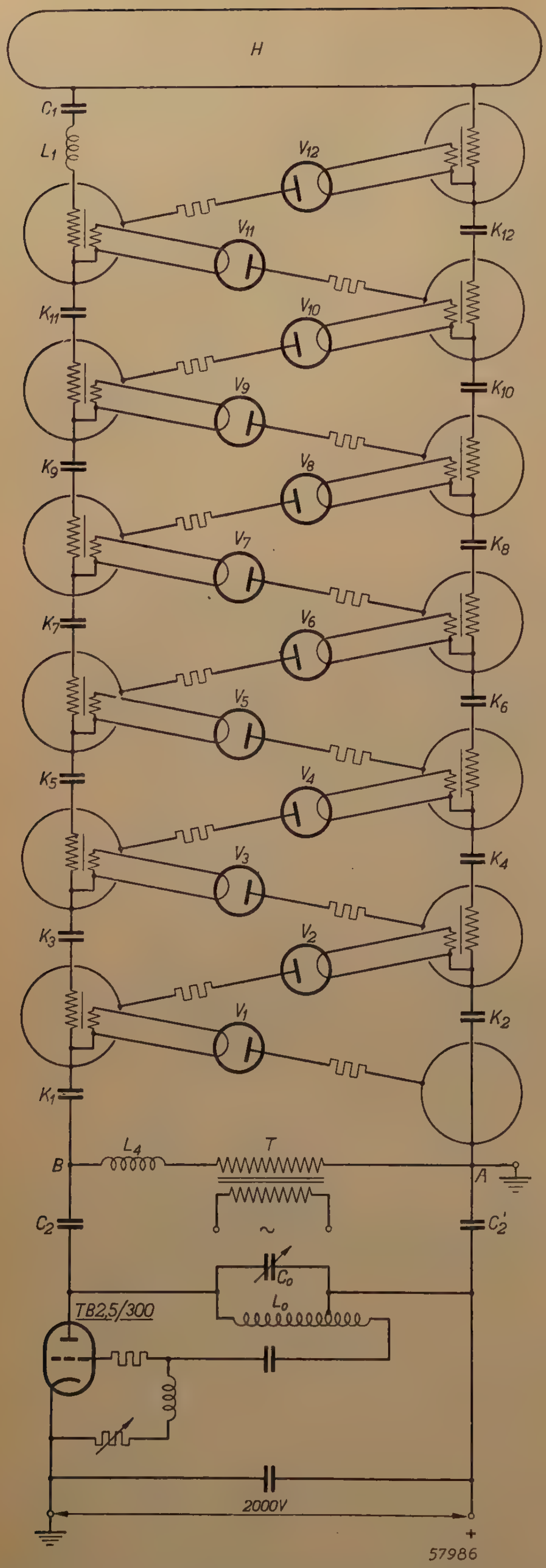


Fig. 9. The new system for feeding the filaments of a cascade generator with h.f. current. The filament circuits are not tuned separately. The oscillator circuit L_0-C_0 is coupled with the cascade generator via two blocking capacitors C_2 and C_2'. The oscillator valve is of the type TB 2.5/300. The output can be varied by about 10% by means of the variable grid resistor.

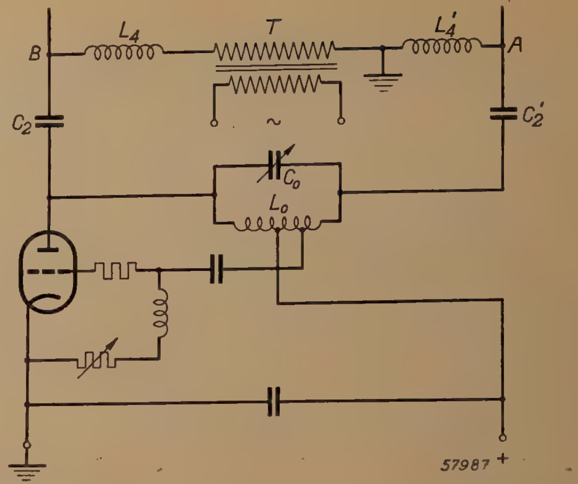


Fig. 10. Oscillator circuit for symmetrical supply. The letters correspond to those in fig. 9. Between A and earth is a second high-frequency choke L_4'.

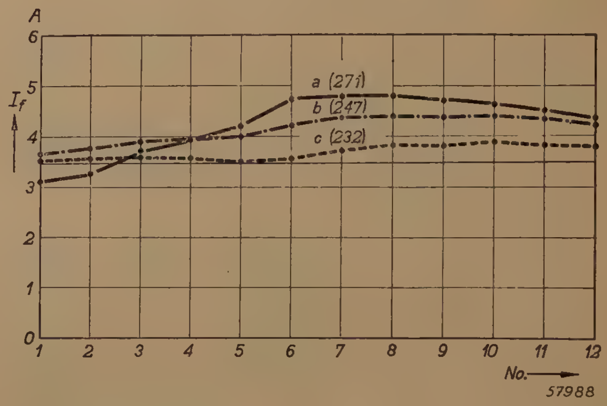
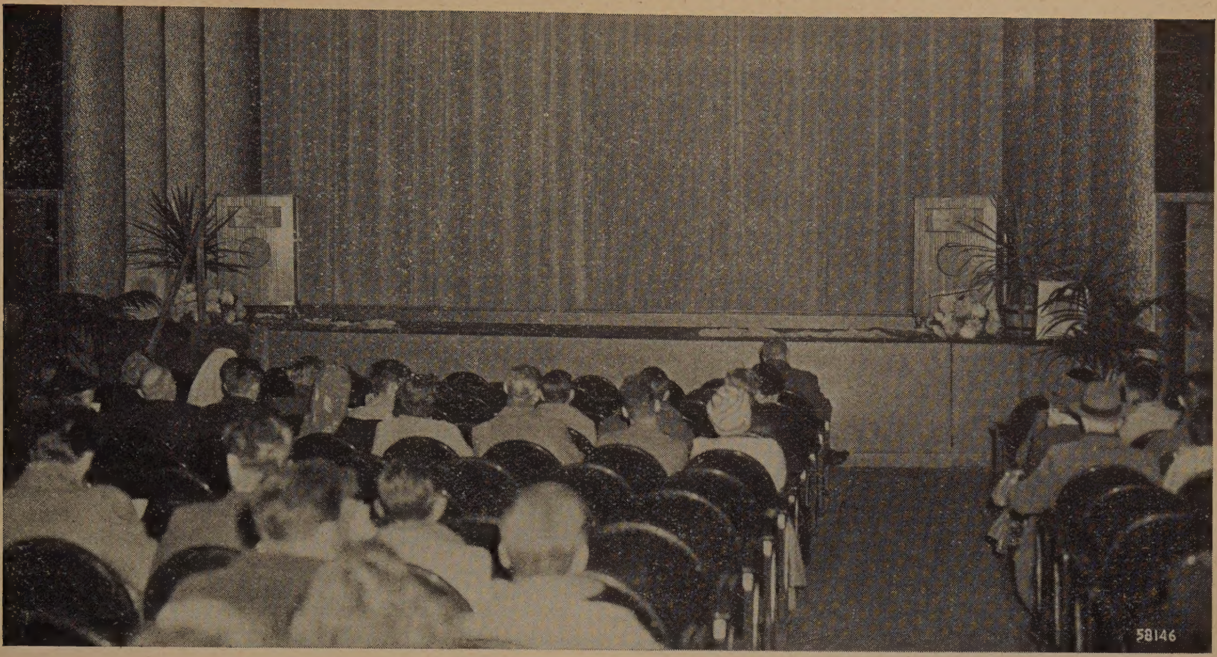


Fig. 11. Measurements taken on a cascade generator with twelve valves. The filament current I_f of each of the valves has been plotted vertically for three frequencies (271, 247 and 232 kc/s). The measured points for the same frequency are connected by straight lines. The frequency of 232 kc/s appears to be the most favourable. The small deviations from the mean level can be compensated with the aid of tappings on the filament current transformers. The mean level itself can be adjusted to the right value (3.5 A) by means of the variable grid resistor of the oscillator.

Summary. When high-frequency current is used for heating the filaments of the valves in a cascade generator one is faced with the difficulty of equalizing the filament currents. The cause of the inequality lies in the capacitance of the metal envelopes placed around the junction points of the cascade generator in order to avoid corona discharges. The lines on which the solution of this problem was at first sought has led to a complicated system in which each filament circuit had to be tuned. In the new system described all these adjustments could be dispensed with, thanks to the low magnetic leakage of the filament current transformers, which are now provided with a core of "Ferroxcube". Thanks to this and other simplifications a system has been devised which, contrary to the old system, is easily adjusted so as to keep all the filament currents within the tolerances allowed and which does not easily become detuned.



STEREOPHONIC MUSIC IN THE CINEMA

534.76:791.45

An experiment was made with stereophonic reproduction of music in a cinema in Eindhoven, the Chicago Theatre, from 29th October to 4th November 1948. In contrast to previous demontrations given in various places to invited guests or in private circles this experiment was carried out as part of a normal public programme.

In this case stereophonic reproduction was applied for the music played during the interval. It is not likely to be applied for the films themselves for some time because film producers must first decide to have the sound track recorded stereophonically, and although this is already possible technically [1] it seems that for the present the alterations necessary in the apparatus and the resultant cost will be considered objectionable. Moreover, the improvement to be expected in the case of films will probably be less striking, since any faulty impression of the direction of the sound is more or less predominated and corrected by the strong visual impression of the picture. When music is played in the interval, however, direction is centered entirely upon the sound itself, particularly so when the music is reproduced mechanically, so that the audience is not distracted by the musicians. It was therefore a promising experiment to apply stereophony for improving the reproduction under these circumstances, so as to eliminate as far as possible the mechanical nature of the music and thus afford the audience an opportunity to enjoy the music as much as if they were listening to an actual concert performance [2]).

There is no need to say much here about the technical execution of the experiment. In the photograph one can see how the two loudspeakers were placed either side of the screen. The music given was selected from a series of stereophonic recordings made by the Electro-Acoustic Department of Philips by the magnetic method.

Everyone in the audience was given a questionnaire on which they were invited to answer three questions:

1) Do you think stereophonic music should be regularly given in cinemas? Answer a) yes, b) not interested, c) no.
2) Do you think that the quality of reproduction demonstrated here is better than that which you are used to hearing in cinemas?
   Answer a) yes, a great difference, b) yes, little difference, c) no.

Space was left on the forms for any further remarks.

Of the 7300 odd forms distributed more than 5800 were returned completed and 500 only partly filled in. About 75 % showed their appreciation, whilst less than 3% were definitely averse to the idea. The table below shows how opinions varied (where a question was not answered it was counted as expressing indifference and included under b).

---

[1] A possibility has been described by K. de Boer, Stereophonic recording on Philips-Miller film, Philips Techn. Rev. **6**, 80-85, 1941; see also R. H. J. Alink, C. J. Dippel and K. J. Keuning, The metal-diazonium system for photographic reproduction, Philips Techn. Rev. **9**, 289-300, 1947.

[2] See the article by R. Vermeulen, Duplication of concerts, Philips Techn. Rev. **10**, 169-177, 1948 (No. 6).

Question	Number of replies a	b	c
1	5764 (79%)	1350	199
2	5548 (76%)	1650	115

In about 800 cases some comments were added, 300 of these expressing enthusiasm, whilst 200 complained that the sound had too sharp a character. In connection with the latter comment it is to be noted that frequencies up to 10,000 c/s were reproduced with less than 2 db attenuation. The public is not accustomed to an unattenuated reproduction of such high notes in mechanical music and there might therefore be a tendency to consider it as being unnatural, unless it were possible to avoid any association with "mechanical music". Other comments made were in respect to the volume of sound, the impression of the stereophonic effect received in unfavourable seats, the selection of the programme, etc.

Although experience teaches that a statistical sounding of the public does not always lead to reliable results, and we shall therefore refrain in this case from giving any comment of our own upon the result of the inquiry, it nevertheless seemed desirable to give publicity to the experiment and its results by means of this communication. An application on a large scale can of course only be expected when a sufficient variety of stereophonic recordings become available for this purpose.

J. P. de VISSER van BLOEMEN.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands.

1845: E. J. W. Verwey, F. de Boer and J. H. van Santen: Cation arrangement in spinels (J. chem. Phys. **16**, 1091-1092, No. 12).

A new calculation of the Madelung constant of the spinel lattice is given, firstly according to Evjen's method and secondly according to that of Ewald. The agreement between the two methods is very satisfactory. The table given is to replace data published previously into which an error of calculation had slipped.

1845a*: G. W. Rathenau: Correspondence on Bowles and Boas's Paper (J. S. Bowles and W. Boas, J. Inst. Metals 74, 753-755, 1948).

This correspondence contains a few remarks by Dr. G. W. Rathenau made in a discussion of the paper indicated. For full particulars the reader may consult an article by G. W. Rathenau and J. F. H. Custers in Philips Res. Rep. 4, 241-260, 1949, No. 4.

1846*: P. Cornelius: Het gerationaliseerde Giorgi-stelsel in de electriciteitsleer (T. Ned. Radiog. **14**, 1-19, 1949 No. 1). (The rationalized Giorgi system in electromagnetism; in Dutch.)

Short survey of the rationalized mks system of electrical units and of a number of familiar formulae as expressed in these units (see these abstracts Nos **1803***, **R 103** and **R 111** and Philips Techn. Rev. **10**, 79-86, 1948).

1847: F. A. Kröger and J. E. Hellingman: Chemical proof of the presence of chlorine in blue fluorescent zinc sulphide (J. Electrochem. Soc. **95**, 68-69, 1949, No. 2).

According to the writers blue fluorescent ZnS contains chlorine, which has been added as a flux (e.g. NaCl) or by preparing the phosphor in an atmosphere containing HCl. A chemical determination of the chlorine in ZnS phosphors, giving 2×10^{-5} to 27×10^{-5} gr atoms/mole ZnS, supports this view. This figure is in fair agreement with estimates of the number of centres in ZnS phosphors. The blue luminescence increases with increasing Cl-content.

1848: J. A. **Haringx**: The cross-spring pivot as a constructional element (Appl. sci. Res. A **1**, 313-332, 1949. No. 3).

This paper deals with the behaviour of the so-called cross-spring pivot, a flexible element connecting two members of a construction and consisting of two flat springs crossing each other at an angle of, for instance, 90 degrees. To a first approximation the pivot point coincides with the "point of intersection" of the two springs. By an elementary calculation one finds the rigidity of the direction of the force to be transmitted. A second calculation gives us the shift of the pivot point occurring for large angles of deflection, though for a pure bending moment only.

1849: J. D. **Fast**: Gasvormende stoffen in de bekledingen van lasstaven (Lastechniek **15**, 189-192, 1949, No. 3). (Gas-evolving substances in the coating of welding electrodes; in Dutch).

During arc-welding CO, CO_2, H_2 and H_2O escape from the coating of the welding electrode. The chief task of these gases consists in imparting a great velocity to the drops of molten metal and in causing a good penetration. The gases liberated, however, may also form a real danger, e.g. by causing porosity, fracturing and brittleness. Especially H_2 is discussed in this connection (see these abstracts, No. **1852**).

1850: H. G. **Beljers**: Measurements on gyromagnetic resonance of a ferrite using cavity resonators (Physica **14**, 629-641, 1949, No. 10).

The phenomenon of gyromagnetic resonance is measured with a resonance cavity, using small spheres and a thin ring made of "Ferroxcube 4", a nickel-zinc ferrite. Samples are placed in a cylindrical cavity at the electric nodal circle of the mode E_{020}. Resonance-frequency shift and quality are measured for various values of the axial magnetic field H.

Some experimental values for the gyromagnetic ratio are deduced. The g-factor was found to be 2.12.

Making some simplifying assumptions, the above-mentioned relation between H and the complex $\Delta\omega$ is calculated and compared with the experimental curve. As could be expected, no quantitative agreement for all values of the magnetic field was found. Some maximum values for the internal damping are deduced from the measurements.

1851*: H. **Bremmer**: Terrestrial radio waves. Theory of propagation (X + 343 p., 91 fig.; Elsevier Publ. Cy, Inc., New York, Amsterdam, London, Brussels, 1949).

The theoretical problem of the propagation of terrestrial radio waves consists in determining the magnitude of the electromagnetic field, and, more especially, the electric field, if the transmitter is a given source of electromagnetic waves. Whereas this problem is comparatively simple for a transmitter in empty space, it becomes rather complicated when the disturbance caused by a spherical earth is taken into account. The problem is then essentially one of diffraction. In addition the influences of the ionosphere and the refraction in the lower part of the atmosphere have to be discussed.

In chapter II-VI, inclusive, of this book the latter influences are entirely ignored, so that the atmosphere is then imagined to consist of empty space. The results obtained in this way apply in those cases where the field caused by the ionosphere (sky wave) is small as compared with the direct field (ground wave). A solution of Maxwell's equations is obtained, assuming constant ε and conductivity (σ) inside the earth, whereas outside $\varepsilon = 1$ and $\sigma = 0$. The transmitter is imagined as a point source, the field being singular at the transmitter. At the surface of the earth the usual boundary conditions (continuity of tangential components of electrical and magnetic field) apply.

The radio problem is mathematically equivalent to a number of problems in optics, acoustics and elasticity, such as scattering of light (Rayleigh), optical phenomena caused by colloidal particles (Mie, Debye), distribution of light in the rainbow (Airy).

In dealing with the vectorial wave problem the investigation of the six components of the electromagnetic field is replaced by the determination of the Hertzian vector, from which all components may be derived by differentation. In this way the originally vectorial problem is reduced to a scalar problem, in which form the solution applies also to acoustical problems such as: diffraction of sound waves round the human head and the acoustics of a spherical dome-shaped vault, and to the geological problem of the propagation of seismic waves. If the inhomogeneity of the atmosphere is taken into account, as is done in chapters VII-XI, inclusive, the problems also bear a close relation to others in a different field, such as reflection of acoustic waves by the stratosphere and the under-water propagation of acoustic waves. Chapter I (introduction) contains the statement of the problem and its connection with other problems, as outlined above, and further an historical account and a general survey. Part 1, dealing with the theory for a homogeneous atmosphere, consists of the following chapters: II) The series of zonal harmonics for the ground wave; III) Watson's transformations and the residue series; IV) Computations by means of the series of residues; V) Geometric optical approximations; VI) Numerical computations and results.

Part 2, dealing with the theory for an inhomogeneous atmosphere, consists of the chapters VII) General considerations; VIII) Geometric optical computations; IX) Computations concerning the field as a sum of "modes"; X) Special applications; XI) Effect of the earth's magnetic field.

In addition figures show the field distribution under various conditions. (See also these abstracts Nos **1790**, **R 97** and **R 108.**)

1852: J. D. Fast: Waterstof bij het booglassen (Laschtechniek **15**, 220-224, 1949, No. 5). (The role of hydrogen in arc-welding; in Dutch.)

This article deals with the influence of hydrogen on the weld metal. Porosity, fracturing and the occurrence of fish-eyes are extensively discussed (see these abstracts, No. **1849**).

1853: K. F. Niessen: Nodal planes in a perturbed cavity resonator, II (Appl. sci. Res. **B1**, 251-260, 1949, No. 4).

Starting from a field with one nodal plane, parallel to one of the walls of the original resonator, a combination of functions analogous to that described in Part I (see these abstracts No. **1815**) is obtained, fulfilling the conditions in the perturbed resonator. It appears that two of these functions must be multiplied by coefficients of the order δ. For the ratio of the coefficients of order 1 two values are found and consequently two solutions for the perturbed field with two different frequencies. Neither of these solutions returns to the original unperturbed function for $\delta \rightarrow 0$. There follows a brief discussion of the behaviour of the nodal plane.

R 102: D. S. Saxon and R. A. Hutner: Some electronic properties of a one-dimensional crystal model (Philips Res. Rep. **4**, 81-122, 1949, No. 2).

The Kronig-Penney model of a one-dimensional crystal is studied further with the aid of the formalism of the Dirac δ-function. Both a Green's-function method and a scattering-matrix method are used to derive the energy levels and wave functions for the monatomic and the diatomic lattices. The scattering-matrix method is used to study the problems of a single impurity, both substitutionally and interstitially located, and of the coupling between impurities. In the last section the general problem of a solid solution is discussed.

R 103: P. Cornelius and H. C. Hamaker: The rationalized Giorgi system and its consequences (Philips Res. Rep. **4**, 123-142, 1949, No. 2).

It is shown in this paper that, if we interpret electromagnetic phenomena by means of field concepts, if we base our arguments on the simplest type of field, namely the homogeneous field, and if we make use of the pronounced analogy between the current field in a conductor, the electrostatic field in a capacitor, and the magnetic field in a coil, we are then led by a straightforward line of argument to the rationalized Giorgi system, which can thus be explained and introduced in a convenient way. By slightly extending these considerations, material properties, such as polarization, susceptibility, can be defined in a consistent and simple manner. It is pointed out that discussions regarding dimensions, "Grössengleichungen", and fundamental and derived units are generally inconclusive and of no interest in practice (see these abstracts No. **1803**).

R 104: K. F. Niessen: Anomalous skin impedance as a function of the field strength (Philips Res. Rep. **4**, 143-153, 1949, No. 2).

The skin effect in a metal of high conductivity is studied in the case of a strong field of high frequency, using Pippard's original assumption of electrons going to and from the surface only in the normal direction. The curvature of the average electron path by the internal field is taken into account in a very simplistic manner, from which a dependence of the anomalous skin impedance on the field strength may be expected, viz. a decrease of the resistivity and an increase of the reactance for an increasing amplitude of the electric field on the surface.